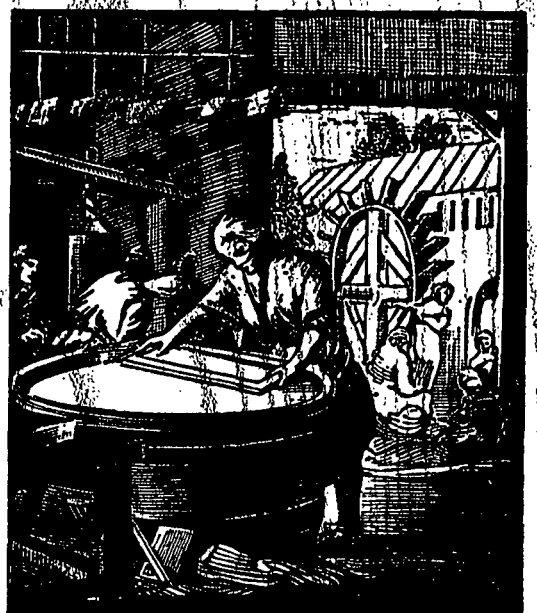

INSTITUTE OF
PAPER CHEMISTRY
Appleton · Wisconsin

PARTICLE RETENTION AT HIGH VELOCITIES IN THIN FIBER MATS

Project 2570

Report Two

A Progress Report

to

MEMBERS OF PROJECT 2570

May 10, 1967

THE INSTITUTE OF PAPER CHEMISTRY
Appleton, Wisconsin

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THE INSTITUTE OF PAPER CHEMISTRY
Appleton, Wisconsin

PARTICLE RETENTION AT HIGH VELOCITIES IN THIN FIBER MATS

SUMMARY

This report covers the work on the hydrodynamic aspects of particle retention which has been done in the past year. This is a continuation of a study which began under Project 2348. The objective of the present work is to extend the understanding of the retention process to the conditions which occur on a paper machine. Thus, most of the experiments which were performed were on the retention of particles by thin pads (basis weight < 100 g./m.^{2}) formed at relatively high velocities (> 10 cm./sec.).

At the more drastic conditions used in the present study, the retention behavior during a constant-rate filtration was more complex than it was in the earlier study. The bound particle distribution showed curvature which could not be explained on the basis of the theory which had been developed. This complication became more pronounced at higher forming velocities. The reason for this behavior is still unknown. Several possible explanations for the effect are given in the report along with some suggested experiments which could differentiate between them.

Some uncertainty was found in measurement of the pre-pad retention. Values of pre-pad retention determined by extrapolation of distribution curves were significantly higher than those determined by direct measurement. This may be due to a higher rate of retention in the region near the mat surface. The pre-pad retention was found to be nearly proportional to the concentration of free particles, which suggests that the pre-pad retention is in a state of equilibrium between free and bound particles. The implications of such an equilibrium was not pursued.

During the course of the study it was found that the particles could increase in size due to flocculation. Colloidal environments which were favorable for retention were also favorable for particle flocculation. The true particle size during any particular experiment is unknown, which makes interpretation of the data quite difficult. A Coulter Counter has been obtained to permit measurement of the particle size distribution under the actual experimental conditions.

Some preliminary retention experiments were made on the Web Former. All of the trends which were observed were in accordance with what was expected from theoretical considerations. This would seem to substantiate the approach that has been taken in this study.

INTRODUCTION

This report, which covers the work of the past year on the retention of particles by fiber mats, is part of the continuing research on the sheet-forming process. The present study is an outgrowth of earlier work on particle retention under Project 2348. The earlier work laid the foundation by uncovering the fundamentals of the retention process. The results of this fundamental study are adequately summarized in the first Critical Review (1). The basic objective of the present work was to extend the study of particle retention to more complex situations which are applicable to conditions on a paper machine.

The retention of small particles by fiber mats is a subject of great importance to the papermaker. Pigments such as titanium dioxide or calcium carbonate are added to the furnish to improve the opacity of the sheet. Clays and other materials are added as fillers and to obtain a surface which is suitable for printing. The retention of fines is of greater or lesser importance on every paper machine since the fines can constitute a significant portion of the fiber furnish and help to fill in the sheet. In many cases the retention of fines is vital in obtaining the desired sheet properties. The fines which are not retained in the sheet go into the white water and eventually are lost from the system. These can be a significant contributor to stream pollution since they can be quite difficult to remove from the white water once they get into it. The retention of fines can also have a pronounced effect on the drainage behavior. The above are some examples of how the retention of small particles by fiber mats is of importance to the papermaker. Because of the importance of this subject and its interrelation with other aspects of the sheet-forming process, it is a natural subject to study under Project 2570.

The retention of small particles is one of the many facets of the sheet-forming process. In general, one can speak of two types of retention. The retention of fibers and other materials of like dimensions is a statistical process governed by the geometry of the fibers and the mesh or web on which they are laid down. The retention of small particles occurs in a different manner. The particles become attached to the surface of the fibers rather than being retained by a geometric arrangement of the fiber mat. Thus, the factors which govern the retention of small particles are quite different from those which govern the retention of fibers themselves. With particles, the colloid chemistry of the system is extremely important since the particles are retained by attachment at the fiber surface, and the forces which govern the attraction are physicochemical in nature.

Although the retention of small particles is ultimately governed by the attractive and repulsive forces which exist between the particle and the fiber, and hence on the colloid chemistry of the system, there are many aspects of the problem which are essentially hydrodynamic in nature. In including a study of particle retention in the sheet-forming project, the understanding was to concentrate on the hydrodynamic aspects of the retention process and to minimize the colloidal aspects. This was to be done by holding the colloidal environment constant at some arbitrary level and studying the effects of hydrodynamic variables. There are many aspects of the retention process which are essentially hydrodynamic and which are significant. The transport processes by which the particles move from the bulk of the fluid to the fiber surface are basically hydrodynamic. The retention rate can be looked upon as made up of two factors. The hydrodynamic factor is involved in the particle transport and the colloidal factor is involved in the determination of whether particles which reach the fiber surface are retained. In addition to the particle transport, other hydrodynamic effects are also important.

The distribution of particles in the sheet is governed entirely by the hydrodynamics of the forming process. The particle distribution in a sheet is important not only from the standpoint of sheet properties but is also a very powerful tool for gaining a better understanding of the retention process.

The ultimate objective of this work is to obtain a sufficient understanding of the processes involved in particle retention so that problems which involve retention on the paper machine can be solved on a rational basis. Ideally, it would be desirable to know enough about the process so that retention could occur at efficiencies approaching 100% and with the distribution of particles within the sheet tailored to give the desired properties. This is, of course, a utopian outlook, but as our understanding of the retention process increases, these goals may eventually be approached.

THEORY OF PARTICLE RETENTION

The basic work on the theory of the retention process was done under Project 2348 and is described in the first Critical Review (1). It is useful to include a brief derivation of the theory in this report since it serves as a ready reference and because the derivation can be done in a somewhat more general manner. A detailed derivation of the retention equation is presented in Appendix I. The important features of these equations will be discussed in this section of the report.

The process of particle retention is treated as essentially a mass transfer process. A distinction is made between free and bound particles. Free particles are associated with the fluid, and if these particles remain as free particles, they are not considered to be retained. Bound particles are particles which are attached to the fiber surface, and are thus associated with the fiber.

Particles which remain bound are considered to be retained. The essence of the retention process is, then, the net mass transfer of free particles to the bound state. Hence, the retention process can be described by the equations for mass transfer in a system in which a fiber mat is formed or present. The mathematical analysis of particle retention is based on continuity considerations, with the allowance for mass transfer between free and bound states of the particles. The basic factor in the validity of the retention equations lies in the applicability of the continuity equations. Fibers are discrete quantities rather than constituting a continuum, and the application of a differential mass balance to such a system is questionable, particularly since the number of fiber layers in a thin mat is on the order of only a hundred. The ultimate test of the validity of the equations rests on their ability to predict experimental data. On an average basis over a sufficiently large area of a mat, the application of continuity equations in differential form is probably valid.

In the original development of the retention equations, the concept of the collection efficiency was introduced. This is a dimensionless quantity which characterizes the rate at which the retention process proceeds. The concept of the collection efficiency was borrowed from the field of aerosol filtration and was applied to the retention of particles by fiber mats. In applying this concept, it was necessary to start by defining the collection efficiency for the ideal case of flow of a particle suspension past a single cylindrical fiber, and then generalize to the case of fiber mats. When the collection efficiency is introduced in this manner, there is some uncertainty that the collection efficiency is applicable to the general case. When the collection efficiency is defined on the basis of an isolated cylinder, it follows that the fiber surface area which is available for retention is the projected area normal to the mean flow. This would mean that

particles are retained on only one side of the fiber, which is not necessarily true. Because of the uncertainty introduced when the collection efficiency is defined on the basis of flow past a single cylindrical fiber, it is desirable to define the collection efficiency in a more general manner.

A generalized definition of the collection efficiency is made in Appendix I in the course of the development of the retention equations. In developing this definition of the collection efficiency, the discrete nature of individual fibers is neglected. The fiber is taken to be a continuum which occupies space and has surface area. Such a treatment of the fiber is implicit in the application of differential continuity equations. One can then consider a differential layer of the fiber continuum past which there is flowing fluid containing particles. The collection efficiency is then defined as the ratio of the net mass flux of particles normal to the fiber surface to the mass flux of free particles past the fiber layer. Defined in this manner, the collection efficiency is seen to be essentially a dimensionless mass transfer coefficient.

In addition to the collection efficiency, the retention rate is also dependent on the surface area of the fiber which is available for retention. While the surface area of synthetic fibers can be defined rather precisely, it is known that the surface of wood fibers is very complex. Thus, when dealing with the retention of particles on pulp fibers, an uncertainty is introduced as to the proper surface area to use. It may be that all of the surface is not available for retention since there may be a phenomenon of active sites or preferential locations for retention. In addition, it is not known conclusively whether the projected area or the total area is subject to retention. This problem can be handled by using the hydrodynamic specific surface as the proper surface area for

retention and absorbing into the collection efficiency all of the factors which account for differences from the true retention surface area. In doing this it is assumed that the true retention area is at least proportional to the hydrodynamic specific surface.

The ordinary z-t coordinate system is not the most convenient one for studying the retention of particles during a filtration process. There are several reasons for this. As filtration proceeds, the surface of the mat moves away from the septum, which is the origin of the z coordinate. Thus, the upper boundary of the mat occurs at continually changing values of z. However, the upper surface of the mat is the location for the boundary conditions on the retention process. This leads to mathematical difficulties. Another problem is concerned with compressible systems (e.g., wood pulp) since in this case the coordinate z does not correspond to a particular fiber layer. In compressible systems, the fibers which are at any position z when the mat is completely formed were not necessarily at this position while the mat was forming. Probably the most important reason is that it is essentially impossible to make experimental measurements with respect to position. For these reasons it is desirable to work with retention equations in a different coordinate system, one in which the coordinates are directly measurable experimentally and in which the important boundary conditions occur at fixed values of the coordinate. A coordinate which fulfills these qualifications is the basis weight of the mat from the mat surface to the point of interest. The origin of this w coordinate system is the mat surface.

The theory of the retention process can be summarized by two basic retention equations, which are derived in Appendix I. These equations, which are essentially continuity equations for free and bound particles are given as follows.

$$-\left\{U_o - \frac{U_f}{(1-\epsilon)} + \frac{\rho_w U_o s\epsilon}{\rho_f(1-\epsilon)}\right\}\frac{\partial P}{\partial w} = \frac{\epsilon}{\rho_f(1-\epsilon)}\frac{\partial P}{\partial t} + S\left\{U_o - \frac{U_f}{(1-\epsilon)}\right\}EP \qquad (1),$$

$$-\rho_w U_o s \frac{\partial P'}{\partial w} = \frac{\partial P'}{\partial t} - \rho_w S\left[U_o - \frac{U_f}{(1-\epsilon)}\right]EP \qquad (2),$$

where:

$\underline{P}$ = free particle concentration, mass particles per unit mass of fluid,

$\underline{P'}$ = bound particle concentration, mass particles per unit mass of fiber,

$\underline{U_o}$ = filtrate velocity,

$\underline{U_f}$ = fiber superficial velocity,

ϵ = porosity,

$\rho_{\underline{w}}$ = fluid density,

$\rho_{\underline{f}}$ = fiber density,

$\underline{s}$ = consistency of suspension, mass fiber per unit mass fluid,

$\underline{w}$ = basis weight coordinate, measured from mat surface,

$\underline{t}$ = time,

$\underline{S}$ = hydrodynamic specific surface of the fiber, and

$\underline{E}$ = collection efficiency.

These two equations are quite general. The only restriction on their validity is the application of differential continuity considerations to fiber mats. The continuity assumption may be considered to be tentatively verified by the application of the same continuity principle to the successful description of flow resistance of fiber mats. Although these retention equations are general and should be of value in describing retention in many different situations, it is impossible to find a general solution which is applicable to all cases of retention.

In order to make use of the equations, it is necessary to make simplifying assumptions and obtain solutions for special cases. The advantage of starting with general equations is that solutions to many special cases can be found, and an appreciation of the factors being neglected is obtained from the assumptions which are made.

SOLUTIONS OF THE RETENTION EQUATIONS

Solutions of the retention equations for some special cases are given in Appendix II. These solutions are obtained for certain ideal situations and are not directly applicable to retention under papermaking conditions. However, examination of the bound-particle distributions which are predicted by theory for the idealized cases is very useful. These special cases act as standards, and the complicating effects which occur under sheet-forming conditions can be studied as deviations from them. In addition, consideration of the distributions which are predicted by theory, and the interpretation of the reasons for these particular distributions helps to give a clearer picture of the factors which govern retention.

PERMEATION

The simplest case which can be considered is the permeation of a preformed mat by a fluid containing particles. In a permeation experiment the fiber mat is formed first, with no particles present. Then a suspension containing particles but no fibers is passed through the mat. The retention process proceeds independent of the forming process. In a permeation experiment, compressibility effects will be negligible and the porosity can be controlled by applying an external load to the mat. The result is that for a permeation with a uniform particle suspension at constant velocity the particle distributions are simple functions.

The distributions which are predicted by theory for a constant-velocity permeation are as follows, for free and bound particles, respectively.

$$P = P_0 e^{-SEw} \qquad (3),$$

$$P' = P_0 t \rho_w U_0 SE e^{-SEw} \qquad (4).$$

P_0 is the concentration of particles in the suspension. It is immediately evident that the distribution of both free particles and bound particles is an exponentially decreasing function of the basis weight coordinate. The concentrations of both types of particles are highest at the mat surface and decrease exponentially away from the mat surface. The exponential decrease in the free-particle concentration occurs because the retention is taken to be a first-order rate process with respect to free-particle concentration. The concentration of bound particles at any particular location in the mat (any w) increases linearly with time. The exponential distribution of the bound particles is identical to the distribution of the free particles. This is because the bound-particle distribution is governed by the retention rate, which is directly proportional to P.

The permeation experiment is basically a simple test to perform. This experimental approach was used in the earlier work in determining the validity of the retention equations. In the original development of the retention equations, the concept of collection efficiency was first applied to permeation and then extended to filtration. One of the most important features of a permeation experiment lies in the many ways in which the collection efficiency can be measured. The SE product can be determined in three different ways. It can be computed from a measurement of the free-particle concentration leaving the pad. It can also be determined from the distribution of the bound particles, and also from the

total retention of particles. A permeation experiment is probably the most sensitive method for determining the SE product.

CONSTANT-RATE FILTRATION

The next simple case to be considered is that of a constant-rate filtration. In this process, a pad is formed at a constant rate from a suspension in which fluid, fiber, and particles are all present simultaneously. Hence, retention occurs simultaneously with mat formation. The constant-rate filtration case is closer to the process which actually occurs on a paper machine, and an understanding of this process is vital to understanding retention under papermaking conditions. In the ideal case of a constant-rate filtration, the retention occurs in a steady-state manner when care is taken to minimize factors which would introduce time effects. The suspension from which the mat is formed must be homogeneous. The process is carried out at low velocity to reduce the stresses on the mat, and hence the compressibility effects. The mat is formed from a low-consistency suspension, since this also acts to reduce compressibility effects.

When all factors which introduce complications into the constant-rate filtration process are kept under control, the distributions can be predicted theoretically. The distributions for an ideal constant-rate filtration are as follows.

$$P = P_0 e^{-SEw} \tag{3}$$

$$P' = P_0' + \frac{P_0}{s}\{1 - e^{-SEw}\} \tag{5}$$

where P_0' is the concentration of bound particles at the mat surface. This is a boundary condition which enters into a filtration process that does not enter into a permeation process. The reason for this is that in a filtration, the

particles and fibers are in intimate contact with one another in the suspension from which the mat is formed, and some retention can occur in the suspension. The amount of retention which occurs prior to mat formation is called the pre-pad retention, $\underline{P}_o'$, and represents a boundary condition for the retention which occurs during pad formation. The pre-pad retention shows up in the particle distribution curve as a constant concentration of bound particles, above which lies the retention which occurs during pad formation. In principle, it can always be determined by extrapolating back an experimental bound-particle distribution curve to zero basis weight.

The particle distributions for an ideal constant-rate filtration process are given by Equations (3) and (5). It is seen that the distribution of free particles is identical with the free-particle distribution obtained for a permeation. The free-particle concentration is highest at the mat surface and decreases exponentially with increasing $\underline{w}$. The distribution of bound particles is, however, of quite different form from that obtained for a permeation. For a constant-rate filtration, the concentration of bound particles is lowest at the upper surface of the mat and increases with basis weight away from the surface until it asymptotically approaches an upper limit according to the exponential function. The exponential behavior is due to the decreasing free-particle concentration with increasing $\underline{w}$, and the upper limit corresponds to the point where no free particles are left. The decrease in free-particle concentration is not the dominant factor which affects the bound-particle distribution. The most important factor is that as a pad is formed by a filtration process, the portions of the mat which are laid down first are subjected to passage by fluid containing particles for a longer period of time than those portions of the mat that are laid down in a later stage in the process. The earlier a given fiber layer is laid down, the

greater the opportunity for it to retain particles. This time factor is not an explicit function but is contained implicitly in the coordinate $\underline{w}$ which is used to describe the filtration process. If the free particle concentration did not decrease in the mat, the distribution of bound particles would be a linearly increasing function of $\underline{w}$, due entirely to the implicit time effect. The exponential in Equation (5) can be expanded in series, and the first term which remains is a linear function of $\underline{w}$. This linear distribution is exactly equivalent to the distribution which would be obtained if the change in free-particle concentration is neglected. Details of this development are given in Appendix II. Thus, if the collection efficiency is low so that the rate of retention is not very great and/or one restricts the examination of the distribution to low values of $\underline{w}$, the bound-particle concentration will be a linearly increasing function of $\underline{w}$. For this case, the distribution of bound particles for a constant-rate filtration can be represented by

$$P' = P_o' + \frac{P_o}{s} SEw \qquad (6) .$$

A good deal of use can be made of Equation (6) when the total retention during pad formation is small (less than 10-20% of the total free particles available). Then the changes in the free-particle concentration can be neglected and the exponential function approaches linearity. Under these conditions, deviations from linear particle distributions can be ascribed to hydrodynamic effects, and the necessary corrections can be added to the bound particle equation. The freedom to neglect changes in free-particle concentration is important in an experimental study of the effect of hydrodynamic factors on retention since it simplifies the analysis of the data. Under these conditions, a plot of experimentally measured values of $\underline{P}'$ vs. $\underline{w}$ should yield a distribution curve from which

an average collection efficiency can be determined from the slope, and the pre-pad retention from the intercept.

The predicted distribution of bound particles in a pad formed by a filtration process such as that described above has been experimentally verified in earlier work at the Institute (1). The expected exponential distributions were found, and collection efficiencies determined from permeation and filtration experiments at similar velocities and ionic conditions were found to agree fairly closely. This indicated the essential validity of the retention equations, and the significance of the collection efficiency. The importance of the particle distribution in the interpretation of retention data was also clearly established.

SATURATION

In some of the earlier work on retention, particularly when fines were retained on wood pulp, a phenomenon which was called saturation was observed. This was a phenomenon in which the particle distribution would obey the theoretical prediction in the regions of the mat near the surface, but at the higher values of w the bound-particle concentration would become constant, even though there were still free particles available. This behavior was termed saturation because the system acted as though the fibers had become saturated with particles and further retention could not occur. This could have been due to the particles occupying all of the active sites, or to a dynamic equilibrium wherein retention was matched by detachment. Saturation is mentioned in this theory section because it represents a complication to the retention process that has been observed previously. It is a difficult problem to get at theoretically without putting a saturation condition arbitrarily into the retention equations. It is shown in Appendix III that saturation, which is characterized by an abrupt break to a constant bound-particle concentration, cannot be predicted by simply including a detachment term

which is first order with respect to bound-particle concentration in the retention equations. Thus, saturation is a more complex phenomenon than a simple equilibrium. The possibility of saturation exists in the work reported herein. Care must be taken in distinguishing saturation from other hydrodynamic effects when analyzing data.

RETENTION ON A PAPER MACHINE

While the special cases described above provide an insight into the types of particle distributions which may be expected under certain circumstances, they are too simplified to be of much use in describing particle retention under conditions which exist on a paper machine. This is because many of the effects which could be ignored for the ideal cases are very important under actual paper-making conditions. The work which has been done before verified the analytical description and confirmed the concept of the collection efficiency. The present task is to extend the treatment and obtain a better understanding of retention under papermaking conditions by making a realistic appraisal of the various contributions to the retention process. The logical place to begin is with a qualitative discussion of the factors which are likely to be of importance on the paper machine but which have been neglected in the simplified treatments presented above.

The formation of a web on a paper machine is basically a filtration process. Thus, the terms which represent the transport of fibers to the upper surface of the mat (the terms in which the consistency is present) must be retained. The filtration process on a paper machine is not a constant-rate process and the filtrate velocity, $\underline{U}_o$, will vary in time. Because of this time variation in velocity, it is expected that the collection efficiency will also be time dependent.

When $\underline{U_o}$ and $\underline{E}$ are time-dependent quantities, there cannot be a steady-state m. solution to the retention equations. In general, under papermaking conditions, the time-derivative terms cannot be neglected.

Another complicating effect is that at the consistencies used on paper machines the compressibility effects during mat formation may not be negligible, since $\underline{U_f}$ may have a significant value. This effect will be most prevalent at the upper surface of the mat since this is the region where the greatest change in porosity occurs.

Another factor is that the sheets that are produced on a paper machine are of relatively low basis weight. With thin sheets, the hydrodynamic boundary effects at both the wire and the upper surface of the mat may influence the retention over significant portions of the mat. The wire can affect retention in at least two ways. First, since the wire stops the flow of fiber, the presence of the wire influences $\underline{U_f}$ and ϵ. As the mat becomes thicker the influence of the wire on the upper portions of the mat diminishes until ϵ approaches time independence at low $\underline{w}$. Thus, the wire causes the porosity distribution (in $\underline{w}$) to change in time as the mat grows until it approaches a limit. A second effect of the wire is a flow convergence effect. Near the wire, the flow will be deviating from its normal path in order to pass through the mesh. Thus, there will be an effect on the fluid velocity in the region near the septum. In some regions the velocity will be locally higher while in other parts there will be regions that are more stagnant. This would be expected to affect the distribution of retained particles.

There is one final complication which must be considered in examining the retention of small particles under papermaking conditions. On a fourdrinier, the drainage is not steady or even continuously varying in a monotonic way. The

drainage tends to be impulsive, as the sheet passes the table rolls, and there is the possibility of back washing on the upstream side of the rolls. This is an exceedingly complex problem to handle, and even approximate methods are not yet available for understanding retention under these conditions. In order to get this understanding, it is necessary to attack the various complications one at a time proceeding from the simplest to the most complex. That is the basis for this study.

RETENTION EXPERIMENTS

In order to extend the study of particle retention to more realistic conditions, it was planned to use the IPC Web Former in a series of retention experiments. Preliminary to running the experiments on the Web Former, a series of constant-rate filtrations were performed on the Dynamic Drainage Tester (DDT). The DDT experiments were to be used to determine quantitatively the effect of velocity on the collection efficiency. This information was then to be used in interpreting the data from the Web Former. In all of this it was assumed that the colloidal conditions could be maintained at a constant level. The intended experimental program is outlined below.

1. Carry out constant-rate filtrations over a velocity range from about 10 to 100 cm./sec. in the DDT. These measurements would be performed for several different colloidal conditions.

2. Determine from these data the effect of velocity on the collection efficiency and determine whether or not the simple filtration equation held for thin pads in this velocity range.

3. Form sheets on the IPC Web Former and determine the distribution of retained particles.

4. Use the data from the DDT in interpreting these data and determine whether there are any unexplained hydrodynamic effects on the Web Former.

Up to the present time it has not been possible to attain these objectives. In part, this is because the retention process is more complicated than the program outlined above would indicate. In part it is due to an inability to

control the colloidal conditions to the degree necessary. It is also due in part to a failure of experimental techniques which earlier work had indicated were adequate. The program was not a total loss by any means. In many respects a better understanding of the retention process was obtained from the difficulties that arose. The program is being modified to study some of the important problems that have been found. This will be made clearer in the following portions of the report as the results of the experiments are discussed.

DYNAMIC DRAINAGE TESTER

The Dynamic Drainage Tester was used to study drainage in Project 2348 and is discussed in detail in those reports and in the Critical Review. Basically, it consists of a 3-in. i.d. flow tube containing a hydraulically driven piston. The full stroke of the piston is 90.2 cm. The speed of the piston is governed by a control valve on the hydraulic system. The piston pushes a suspension of fibers, fluid, and particles through the tube and across a septum, thus generating a constant-rate filtration process. The speed of the piston can be varied from about 5 to 100 cm./sec. With the original DDT, the suspension was introduced above the piston. The piston was driven vertically upward in the tube and the pad was formed on the underside of a septum at the top of the tube. In retention studies it is necessary to remove the pad which is formed intact, so that the particle distribution can be measured. All attempts to do this when the mat was formed on the underside of the septum failed. It was found necessary to form the pad on the upper side of a septum in order to remove the pad intact. It was not possible to drive the piston downward without extremely extensive modification of the entire system. Thus, a 180° bend was attached to the top of the original DDT so that the piston could be driven upward and yet the mat could be formed on the top side of the septum. The diameter of the bend is about 16 inches and it

followed by a 6-inch straight section before the septum assembly is reached. A vent is located at the top of the bend to allow air to escape when filling and to allow air to enter the flow tube when draining. The flow tube is filled from both sides of the bend. The suspension is made up in an open stainless steel tank with a capacity of 250 liters. This tank is located on a mezzanine about six feet above the highest point of the DDT. The insides of the tank have been sprayed with a Teflon film to help prevent the particles from sticking to the side of the tank. The suspension flows to the DDT by gravity from the bottom of the tank through a large plastic hose. A globe valve is located next to the DDT for controlling the filling process.

MATERIALS

The particle which was chosen for the retention work was TiO_2. There were several factors which influenced this choice. Methods for analyzing TiO_2 in fiber mats had been developed in earlier retention work at the Institute. A good supply of particles which had been previously characterized was available. A method of dispersing these particles to obtain minimum particle size had been developed. Finally, TiO_2 is of direct interest to papermakers as an opacifying agent. The fiber which was used in the retention work is a classified (to remove the fines) Weyerhaeuser bleached sulfite pulp. A rather long fiber was used to reduce the specific surface and allow filtrations at high velocities without excessive pressure drop. The colloidal conditions were controlled by maintaining a certain concentration of sodium chlorite in the suspension. It was known from earlier work on retention that a sufficiently high concentration of salt or some other ionic species was necessary in order to obtain a measurable amount of retention. Distilled water was used in all of the DDT work. Reagent-grade sodium chloride was used for control of colloidal conditions. No retention aids

or dispersants were used. A large supply of particles was prepared by dispersing the TiO_2 in a malted-milk mixer for about fifteen minutes at a concentration of 73% solids. This was then diluted with distilled water to make a suspension containing around 1000 g. TiO_2 per liter. This suspension was kept in a constantly rotating bottle to prevent the particles from settling and agglomerating. A second bottle of TiO_2 suspension was prepared from the first and also kept rotating. This was made up periodically and was on the order of 10 g. TiO_2 per liter. A certain volume of the dilute particle suspension would be added to the mixing tank to give the desired concentration for the retention runs.

OPERATION

In making up a suspension for a retention experiment, the tank was first filled with distilled water and then the desired amount of salt was added. The stirrer in the tank was turned on at this point. The required amount of pulp was then weighed out and dispersed on a British disintegrator. The fiber was then added to the tank. Finally, the desired volume of the dilute TiO_2 suspension was added slowly to the tank and left to stir until the mixture was homogeneous. At this point the system was ready for the experimental run. Two men are required for a DDT experiment. One man is stationed on the DDT platform to close the vent and fill valves, start the recorder, and handle the mat-removal operation. The second is stationed down on the floor and operates the valve that controls the flow from the tank and the piston start-stop control. Two men are required because it is necessary to perform all operations quickly once a run has begun. At the high salt concentrations needed to get reasonable retention, the fiber tends to rapidly form flocs and settle out. In order to prevent this fiber flocculation, it is necessary to fill the DDT quickly (filling takes about 10 sec.), and run the filtration immediately after the system is filled. Before the system

is filled, about 4 liters of slurry are run to the drain at the fill valve. This is to remove the suspension that has sat in the lines, which has undoubtedly flocculated, and which may give poor results. The system is filled from both sides of the U bend. On the septum side, filling is done through the same opening from which the excess slurry is drained after the pad is formed. The septum opening is sealed by a spring-loaded rubber stopper across the bottom of the septum. A filtration is initiated by releasing the stopper and starting the piston.

During a run, the pressure upstream of the septum is measured with a strain-gage pressure transducer and recorded on a dynograph. This allows a measurement of the pressure drop across the pad at any stage in the formation and also records the time that the filtration proceeds, from which the velocity is computed. After the filtration is completed a plug is held by hand beneath the septum to act as a seal. The vent valve and the drain valve are then opened and the suspension that remains above the pad is drained off. After this draining is completed, the small amount of suspension that remains above the pad, a depth of about 2 cm., is drained slowly through the pad. The septum and pad are then removed from the DDT. After the pad and septum are removed from the DDT the pad is couched off onto blotting paper under mild pressure and the pad and blotting paper are stored in a Petri dish in a cold room to await further treatment.

PAD ANALYSIS

The normal method of analyzing for the distribution of the TiO_2 in the pads was to split the pads into layers on the Beloit sheet splitter and then analyze the layers for fiber content and TiO_2. The fiber content is determined by drying and weighing. The TiO_2 is determined photometrically using an

AutoAnalyzer. In the cases where the whole pad was analyzed without being split, the couching step was omitted and the pad was scraped off the septum and put directly into crucibles for analysis. The procedure for the analysis is quite complicated and will be described in detail.

1. The sample is dried in a vacuum oven at 60°F. and then weighed.

2. The sample is then ashed in a muffle furnace to get rid of the fiber. A temperature program for the ashing step has been determined so that the ashing proceeds without losing TiO_2.

3. The TiO_2 remaining is then dissolved by heating with 10% sulfuric acid and $(NH_4)_2SO_4$. The solution is then transferred to volumetric flasks and diluted to volume with 10% sulfuric acid.

4. The solution containing the TiO_2 is then run on the AutoAnalyzer where it is mixed with 3% hydrogen peroxide and the colorimetric (photometric) determination is made.

The analysis is quite time consuming, and it normally takes from three to four days before the results of a particular experiment are known. In a situation where the next experiment must await the results of the previous one, this delay can be a problem.

The pads were split on the Beloit sheet splitter. The Beloit splitter works on a differential freezing principle. The sheet moves between two cold rolls and freezes to both rolls. As the sheet passes through the rolls it comes apart in the zone where the pad is not yet frozen. With this device the ability to get good splits is strongly dependent on moisture content and distribution in the sheets and the pressure on the rolls. The long fiber used in the retention

work hindered the ability to split the sheet evenly along fiber layers. Moisture was the most critical parameter. If the sheet was too dry, it did not stick to the rolls and would pass through without splitting. If the sheet was too wet, a great deal of water would be squeezed out of the sheet and the split could be very uneven. In all cases where a split was obtained, some water was squeezed out of the sheet. This led to the question of how the splitting process affected the distribution of particles in the sheet. Since there is relative motion of fiber and water during splitting, the possibility of a redistribution of particles is present. This is complicated by the fact that the water tends to flow in the plane of the sheet as the pad passes through the nip between the rolls. This question of a redistribution of particles during the splitting process plagued the work on retention, and has not yet been conclusively resolved.

RESULTS OF EXPERIMENTS

EFFECT OF FORMING VELOCITY

The first set of experiments on the DDT were a series of constant-rate filtrations at various velocities. Full-stroke pads (100 g./m.^{2}) were formed at a series of velocities, two pads at each velocity. Six different velocities were run, ranging from about 8 cm./sec. to about 32 cm./sec. They were run in sequence, starting with the lowest velocity and ending with the highest. All pads were formed from the same suspension. The data are presented in Table I and the results shown in Fig. 1.

In the section on retention theory, it was indicated that the proper coordinates for a particle distribution curve are the bound-particle concentration, $\underline{P}'$, and the basis weight coordinate, $\underline{w}$. In a case where the area of the sample is always the same, such as on the DDT, the basis weight can be replaced by the fiber mass, $\underline{m}$. This fiber mass coordinate is defined by the relationship $\underline{m} = \underline{w}\underline{A}$, where $\underline{A}$ is the cross-sectional area of the sample. In all of the DDT experiments, $\underline{m}$ was the quantity which was actually measured and is used in the figures. As far as the shape of distribution curves is concerned, it is completely equivalent to $\underline{w}$. Only if numerical values of collection efficiency are to be computed from the curves, or if the cross-sectional areas of the samples differ, must the basis weight be used.

The objective of the experiment was to determine the effect of the forming velocity on the collection efficiency. According to the simplified theory, the data should have plotted up as straight lines, so the collection efficiency could be determined from the slope and the pre-pad retention from the intercept. Examination of Fig. 1 shows that the plots are not straight lines and that a great

TABLE I

DATA SHOWING EFFECT OF FORMING VELOCITY ON PARTICLE DISTRIBUTION

(The suspension was made up as follows: 250 liters of distilled water, 25 g. of fiber, o.d. basis, 150 g. of reagent-grade NaCl, and 1.25 g. of TiO_2, 5% on the fiber.)

Pad		$\underline{U}_p$, cm./sec.	Fiber, mg.	TiO_2, mg.	$\underline{P}'$ x 10^2, mg./mg.	$\underline{m}$, mg.
1A1	top	8.23	112.8	1.27	1.126	56.4
	-		101.6	1.35	1.329	163.6
	-		114.4	1.65	1.442	271.6
	septum		145.5	2.13	1.464	401.6
1A2	top	8.15	101.3	1.10	1.086	50.7
	-		94.3	1.22	1.294	148.5
	-		123.3	1.82	1.476	257.3
	septum		158.2	2.43	1.536	398.0
2A1	top	14.7	101.7	1.10	1.082	50.9
	-		87.7	1.09	1.243	145.6
	-		125.7	1.71	1.360	252.3
	septum		164.7	2.33	1.415	397.5
2A2	top	14.5	108.0	1.15	1.065	54.0
	-		99.3	1.27	1.279	157.7
	-		120.6	1.14	0.945	267.6
	septum		157.0	2.09	1.331	406.4
3A1	top	19.3	106.0	1.12	1.057	53.0
	-		95.1	--	-	153.6
	-		113.5	1.49	1.313	257.9
	septum		157.1	2.01	1.279	393.2
3A2	top	19.3	102.6	1.07	1.043	51.3
	-		90.8	1.12	1.233	148.0
	-		124.5	1.66	1.333	255.7
	septum		163.6	2.15	1.314	399.7
4A1	top	24.5	122.3	1.27	1.038	61.2
	-		80.4	0.95	1.182	162.5
	-		105.2	1.66	1.578	255.3
	septum		163.2	2.03	1.244	389.5
4A2	top	24.2	126.3	1.35	1.069	63.2
	-		94.7	1.14	1.204	173.7
	-		113.1	1.43	1.264	277.6
	septum		161.3	2.03	1.259	414.8
5A1	top	27.7	106.1	1.06	0.999	53.1
	-		89.8	1.01	1.125	151.0
	-		113.8	1.34	1.178	252.8
	septum		151.6	1.76	1.161	385.5
5A2	top	27.7	100.0	0.98	0.980	50.0
	-		88.9	0.99	1.114	144.5
	-		122.5	1.42	1.159	250.2
	septum		147.2	1.65	1.121	385.0
6A1	top	32.1	105.5	1.02	0.967	52.8
	-		91.0	0.97	1.066	151.0
	-		116.9	1.29	1.104	255.0
	septum		159.9	1.74	1.088	393.4
6A2	top	32.1	103.9	1.00	0.962	52.0
	-		95.5	1.02	1.068	151.7
	-		113.5	1.24	1.093	256.1
	septum		141.5	1.54	1.088	383.7

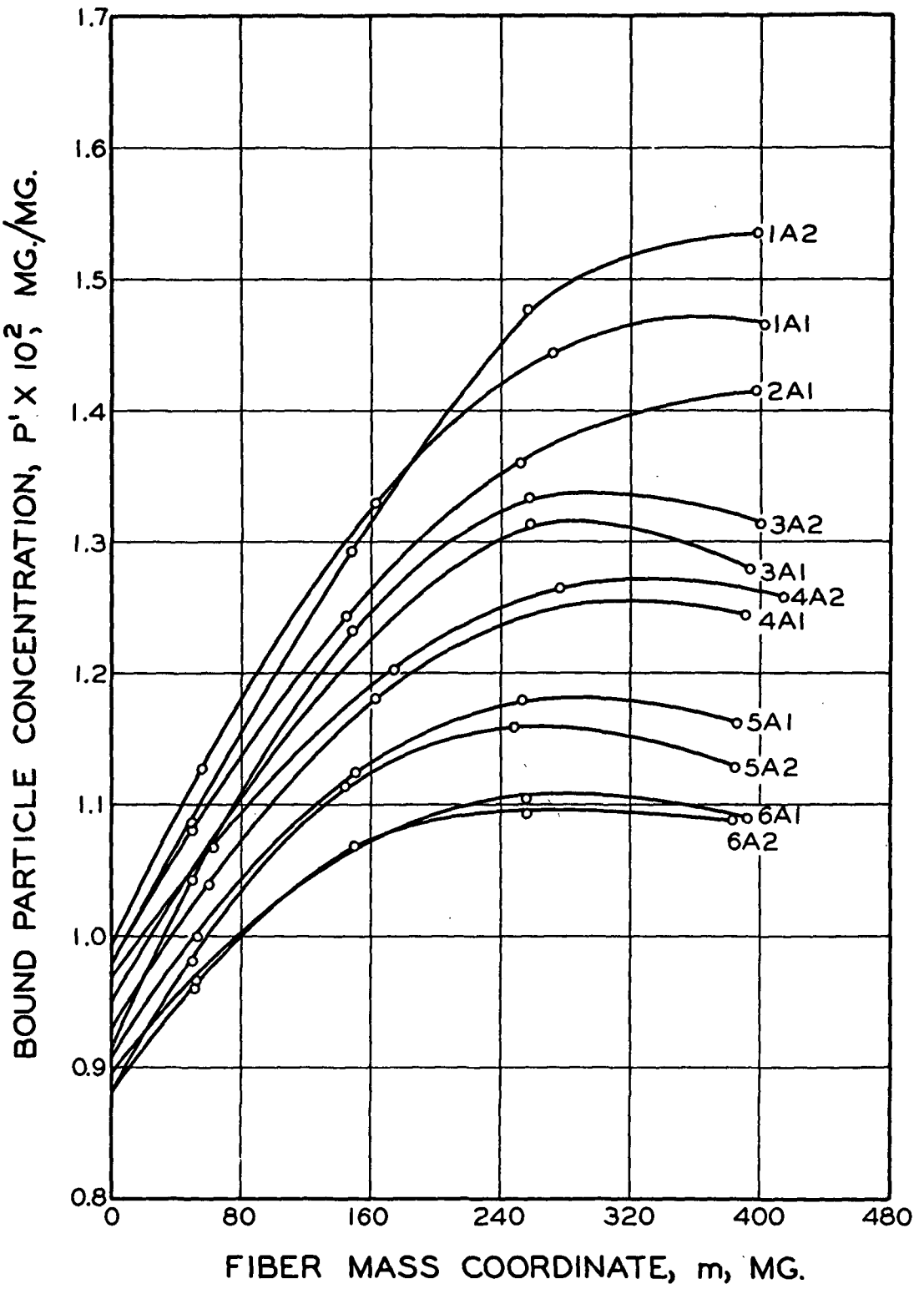

Figure 1. Effect of Filtration Velocity on Particle Distribution Curves

deal of curvature is present. It also indicates that from 60 to 80% of the total retention occurred as pre-pad retention. The curvature of the data is not due to the exponential effect. The total decrease in free-particle concentration from the mat surface onward was less than 20% in all cases. In this region, the exponential function is essentially linear. The fact that the curves are not straight lines means that Equation (6) is not applicable. The curvature represents a non-constant value of the collection efficiency, and the time term in the retention equation may be important. Since the collection efficiency was not solely a function of the velocity but varied within the pad, and equations for handling this case are not yet available, no quantitative determination of the collection efficiency was made.

Several distinct trends are apparent in the data. As the velocity is increased, the total retention becomes smaller. The slope in the region near the mat surface is highest for the lowest velocity and decreases as the velocity is increased. The flattening and possible downturn becomes more pronounced as the velocity is increased, and pronounced curvature seems to set in closer to the mat surface. The reproducibility of the distribution curves for duplicate pads is reasonably good, but the precision is inadequate for detailed study of the complicating effects introduced by the lack of ideality. The pre-pad retention as determined from the intercepts of the extrapolated distribution curves decreases with increasing velocity. This is suspicious behavior. True pre-pad retention should be unaffected by the velocity during pad formation. Since the high-velocity runs were made later in time, it was expected that they might have higher values of the pre-pad retention. The highly curved distributions indicated by these data means that hydrodynamic factors are more important in retention than had been expected. The significance of the curves shown in Fig. 1 will be discussed

more thoroughly later on in this report. Runs 2A2 and 4A1 show distributions which are highly suspicious and are most likely due to errors that crept in during the analysis procedure. The curve for the first one is omitted entirely, while that for the second has the third point omitted.

EFFECT OF PARTICLE CONCENTRATION

The second set of experiments on the DDT was a series of twelve pads formed at the same velocity from the same tank of suspension but the concentration of TiO_2 was varied. The tank was calibrated so that the amount of suspension remaining in the tank could be determined by measuring the height from the top of the tank to the surface of the suspension. The suspension was made up as usual, and additional TiO_2 was added in increments during the course of the run. The suspension was at 0.01% consistency and 10^{-2}M salt concentration. TiO_2 was added in 200-cc. increments from a slurry containing 2.58 g. TiO_2 per liter. The first portion of the TiO_2 slurry was put in the tank about 15 minutes before the first pad was formed. After three pads had been formed the level in the tank was measured and another portion of the TiO_2 slurry was put in. After an additional three pads had been formed, the procedure was repeated again, and so on until a total of twelve pads had been formed. These twelve pads were split on the Beloit sheet splitter to determine the distribution of TiO_2 in the pads. The net result of the experiment was particle distribution curves for twelve pads formed from a single suspension at a constant velocity, with three pads at each of four levels of TiO_2 concentration. The objective was to determine if the retention was directly proportional to the concentration of TiO_2 as the concept of the collection efficiency demands. The results are given in Table II and are plotted in Fig. 2 and 3.

TABLE II

DATA SHOWING EFFECT OF PARTICLE CONCENTRATION ON RETENTION

(The suspension was made up as follows: 250 liters of distilled water, 25 g. of fiber, o.d. basis, 150 g. of reagent-grade NaCl, TiO_2 added in 200-cc. increments from a slurry containing 2.58 g. TiO_2/liter. U_o = 20.9 cm./sec. for all pads.)

Pad		$P_{oo} \times 10^2$	Fiber, mg.	TiO_2, mg.	$P' \times 10^2$, mg./mg.	m, mg.	$P'/P_{oo} \times 10^2$
1C1	top	2.06	203.9	0.40	0.196	102.0	10.32
	-		107.9	0.25	0.232	257.9	12.21
	septum		137.9	0.34	0.247	380.8	13.00
1C2	top	2.06	110.8	0.18	0.162	55.4	8.53
	-		93.3	0.16	0.171	157.5	9.00
	-		114.0	0.25	0.219	261.1	11.53
	septum		128.9	0.31	0.240	382.6	12.63
1C3	top	2.06	130.9	0.26	0.199	65.5	10.47
	-		85.0	0.18	0.212	173.4	11.16
	-		105.5	0.26	0.246	268.7	12.95
	septum		116.9	0.34	0.291	379.9	15.32
2C1	top	4.46	122.6	0.47	0.383	61.3	9.36
	-		104.5	0.42	0.402	174.9	9.83
	-		95.2	0.43	0.452	274.7	11.05
	septum		144.6	0.71	0.491	394.6	12.00
2C2	top	4.46	109.2	0.48	0.440	54.6	10.76
	-		94.9	0.48	0.506	156.7	12.37
	-		110.4	0.63	0.571	259.3	13.96
	septum		123.4	0.71	0.575	376.2	14.06
2C3	top	4.46	120.4	0.47	0.390	60.2	9.54
	-		86.2	0.37	0.429	163.5	10.49
	-		98.9	0.48	0.485	256.1	11.86
	septum		137.1	0.71	0.518	374.1	12.67
3C1	top	7.35	109.3	0.74	0.677	54.7	10.09
	-		93.4	0.73	0.782	156.0	11.65
	-		104.7	0.91	0.869	255.1	12.95
	septum		132.9	1.19	0.895	373.9	13.34
3C2	top	7.35	120.8	0.82	0.679	60.4	10.12
	-		89.2	0.71	0.796	165.4	11.86
	-		84.3	0.71	0.842	252.2	12.55
	septum		147.0	1.33	0.905	367.8	13.49
3C3	top	7.35	113.6	0.82	0.722	56.8	10.76
	-		81.5	0.68	0.834	154.4	12.43
	-		100.5	0.94	0.935	245.4	13.93
	septum		139.6	1.36	0.974	365.4	14.52
4C1	top	10.95	112.4	1.11	0.988	56.2	9.84
	-		108.2	1.22	1.128	166.5	11.24
	-		104.9	1.32	1.258	273.1	12.53
	septum		113.2	1.44	1.272	382.1	12.67
4C2	top	10.95	110.8	1.07	0.966	55.4	9.62
	-		83.2	0.94	1.130	152.4	11.25
	-		102.7	1.25	1.217	245.4	12.12
	septum		144.7	1.86	1.285	369.1	12.80
4C3	top	10.95	107.5	1.08	1.005	53.8	10.01
	-		80.9	0.95	1.174	148.0	11.69
	-		92.4	1.19	1.288	234.6	12.83
	septum		151.2	2.03	1.342	356.4	13.37

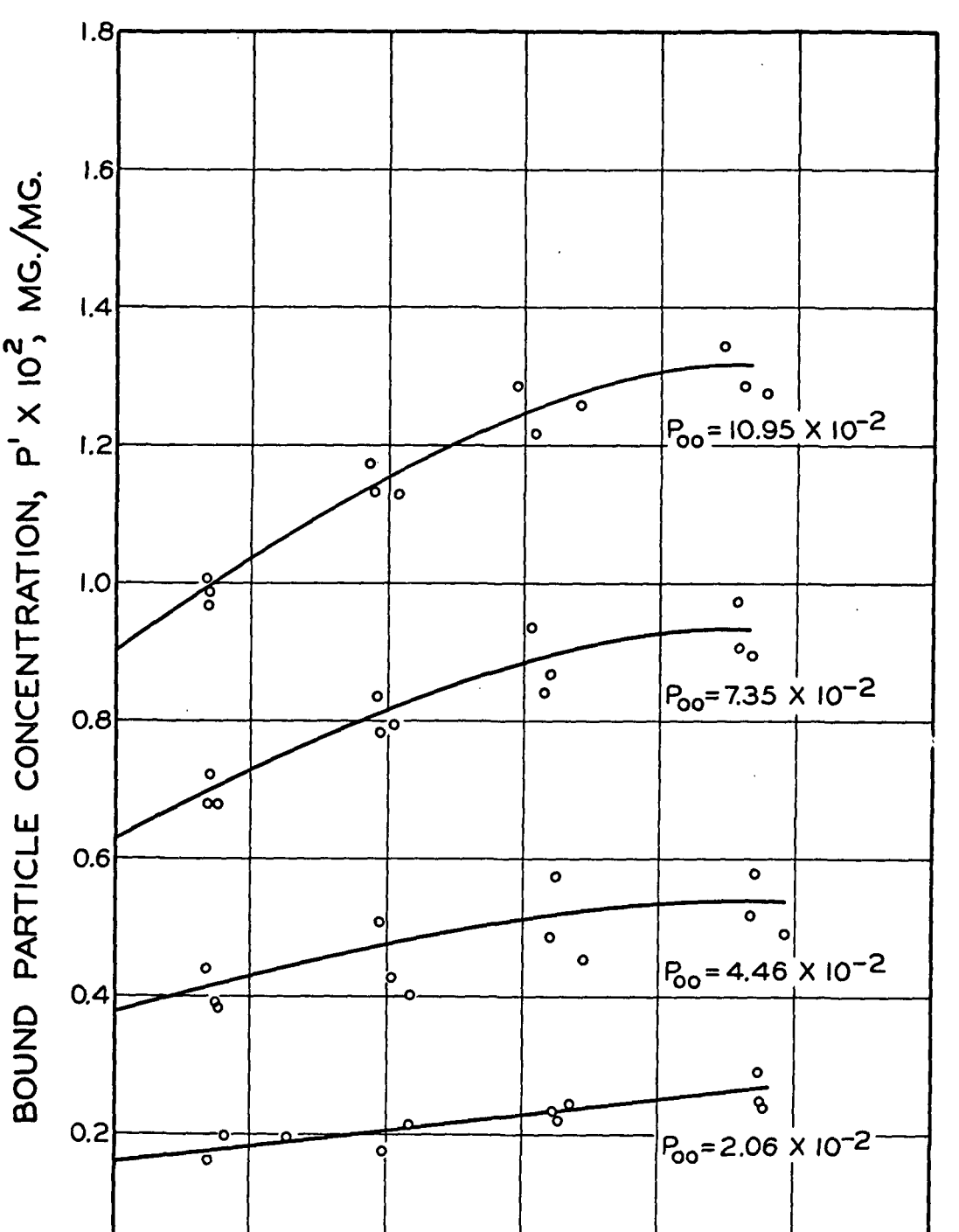

Figure 2. Effect of Total Particle Concentration on Particle Distribution Curves

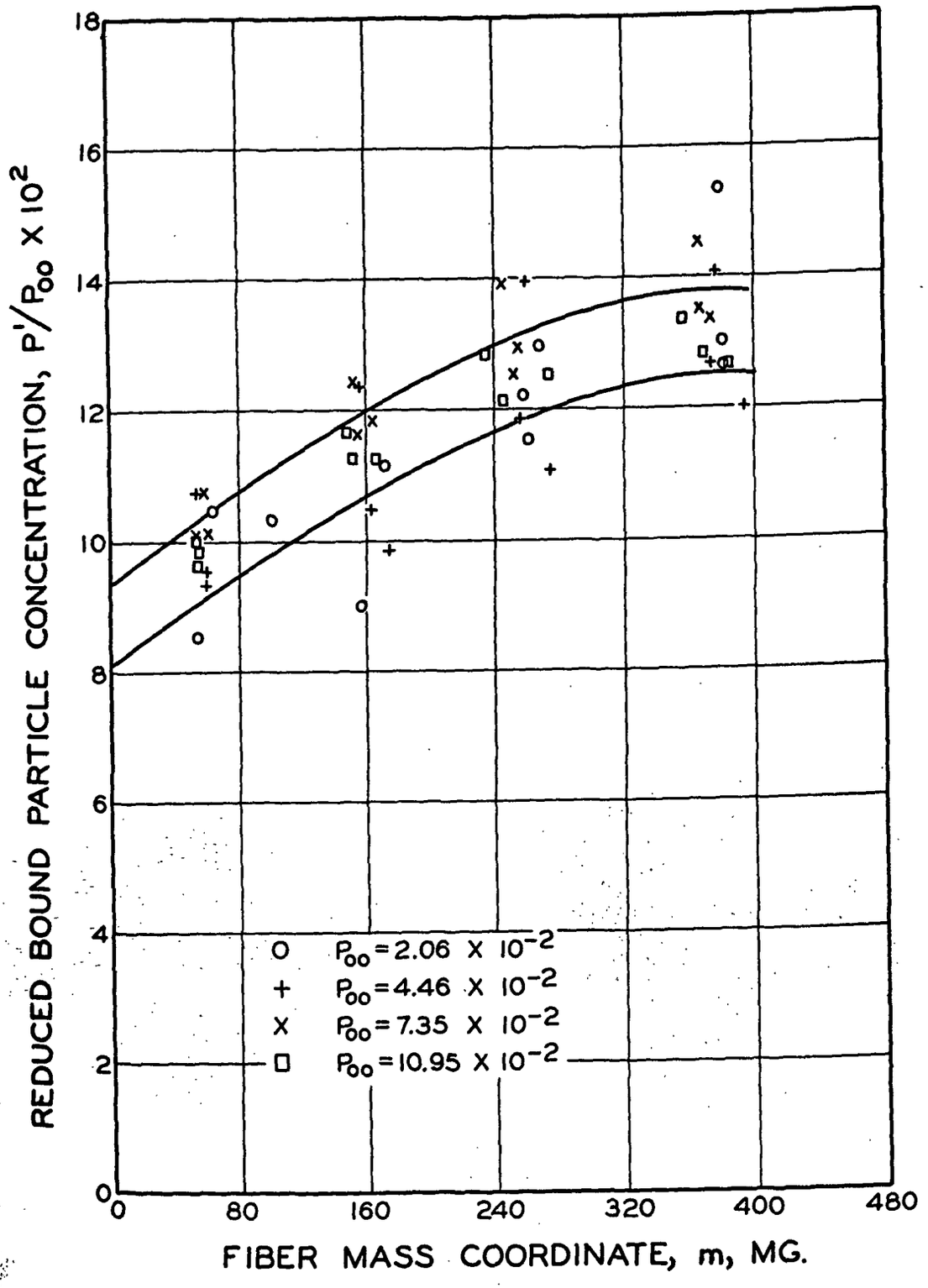

Figure 3. Particle Distribution Data Presented as Percent of Total Particles Available

These data show some interesting features. In Fig. 2 the curves fall into four distinct groups which correspond to the four levels of particle concentration. Both the slope and the intercept of the curves increase as the concentration of particles increases. This is in the direction indicated by the concept of the collection efficiency. There is a good deal of scatter in the data for the mats formed at the same level of particle concentration. The scatter does not show a consistent trend with the order in which the pads were formed and is thus apparently not some kind of systematic effect. The distribution curves are not straight lines, and in general seem to have the same shape as the first set of data discussed earlier. Again, there are a few points which are obviously in error, due to problems in splitting or in the analytical procedure. Because the distribution functions were curved, the collection efficiency could not be determined from the slopes. Thus, a comparison of the collection efficiency at the different concentrations of particles could not be made quantitatively.

The effect of particle concentration on retention is shown in Fig. 3. In Fig. 3, the bound-particle concentrations are divided by the total particle concentration, $\underline{P}_{oo}$. $\underline{P}_{oo} = \underline{P}_o' + \underline{P}_o/\underline{s}$ and is the total particle concentration in the tank expressed as mass of particles per unit mass of fiber. To rigorously test the concept of the collection efficiency, the bound-particle concentration should be reduced by the free-particle concentration $\underline{P}_o/\underline{s}$. This is complicated by the difficulty in determining $\underline{P}_o'$, and at the low levels of retention which occurred, $\underline{P}_{oo}$ is a reasonable approximation. $\underline{P}_{oo}$ was used since it was directly measured.

Although all of the data were not reduced to a single curve, they did all fall within a narrow region without showing any systematic variation with particle concentration. Detailed examination of the data for the individual pads indicates

that they have about the same shape and slope and differ mainly in the position of the intercept. Since the slopes are determined by the conditions during mat formation, and the intercept by the pre-pad retention, the scatter is apparently due mostly to variations in pre-pad retention. Thus, the retention during pad formation was proportional to the concentration of the particles. Therefore, it may be considered that the essential validity of the concept of the collection efficiency has been further established.

The data on the effect of velocity and particle concentration on the distribution of retained particles in mats formed by a constant-rate filtration process indicated that hydrodynamic aspects of the retention process were more prevalent and significant than had been expected from the earlier work. In general, the amount of retention which occurred during pad formation decreased significantly when the velocity was increased. There was a good deal of curvature in the distributions which could not be accounted for by any of the simplified special cases of retention in a filtration process. This was apparently due to hydrodynamic effects which had not been accounted for in the simpler theories. In general, the curvature became more pronounced as the velocity increased. The retention rate seemed to be directly proportional to the particle concentration as required by the theory based on the concept of the collection efficiency. There was a good bit of scatter in all of the data, and the reproducibility from one pad to the next was not very precise. It was suspected that the sheet-splitting process may have caused some redistribution of the particles in the mats and could account for some of the scatter in duplicate runs. There was also a question of obtaining the pre-pad retention by extrapolating curves since a maximum of only four points was available to form the curves and make the extrapolation. Once the data did not fall along the theoretical straight line, extrapolation was subject to uncertainty.

PRE-PAD RETENTION

A set of experiments was made to investigate pre-pad retention by measuring it independently of the forming process. Two factors must be satisfied to make such a measurement. One must obtain enough fibers and retained particles so that the measurement can be made accurately and be statistically significant. The second requirement is that the separation of fibers from the suspension must be done in such a manner that there is no change in the bound-particle concentration during the separation process. In any method of selectively removing the fibers from a suspension there will be some relative motion of fibers past fluid containing particles. Thus, there is always the potential of changing the quantity which is to be measured by the method of measuring it. There seem to be two ways of approaching this problem. One method of measuring the pre-pad retention is to form a sheet of very low basis weight but of sufficient area so that the total sample is large enough to be measured. A second approach is to remove the fibers from the suspension with as little disturbance as possible. A method for doing this would be to put the suspension into a cylinder, allow the fibers to settle by gravity, siphon off the fluid containing the free particles, filter the thickened suspension, and then analyze for particle and fiber content. Both approaches were taken in the experiment on pre-pad retention.

A full tank of suspension was made with 0.01% consistency, salt concentration of 10^{-2}M, and TiO_2 concentration 3.6% on the fiber. Pads were formed in the usual manner on the DDT. A total of six pads were formed at three different velocities, two pads at each velocity. These were split and analyzed, and the distribution curves obtained. From the distribution curves an estimate of the pre-pad retention by extrapolation could be made for comparison with values determined by other means. Four other measurements of the pre-pad retention were made for

each set of pads. A portable sheet mold with a diameter of 6 inches (compared with the septum diameter of 3 inches on the DDT) was used to form sheets of low basis weight. Thin sheets were formed from both one and two quarts of suspension to give basis weights of about 10 and 20 g./m.^{2}. In addition, pre-pad retention was also measured by settling with 1 and 2 liters of suspension. Two pre-pad measurements were made from the suspension after each pad was formed, one by a low-basis-weight pad and one by settling. These would be of alternate volume, and the volumes would invert after each test. Thus, for each velocity, two ordinary pads were formed, and four independent measurements of the pre-pad retention were made. The data are presented in Table III and the distribution curves are shown in Fig. 4. The values of the pre-pad retention determined by extrapolating the curves and those measured by the other techniques are tabulated in Table IV so that a comparison between the various methods can be made.

It can be seen that a significant difference exists between the values of the pre-pad retention determined by extrapolating distribution curves and those determined by the other methods. The extrapolated values are much higher than any of the other measurements. The lowest values of the pre-pad retention were obtained on the sheet mold when the smallest amount of suspension was used. The settling measurements tended to give values slightly higher than did the low-basis-weight pad measurements. All four of the independent measurements of the pre-pad retention were much lower than values from the extrapolated distribution curves. There could be at least three possible causes for this large discrepancy. If there is redistribution of particles during the sheet-splitting process, it could tend to flatten the distribution and make it more uniform. This would cause the value of the pre-pad retention measured by extrapolation of the distribution curves to be higher than the true value. A second possibility is that the retention rate

TABLE III

DATA FROM EXPERIMENT TO DETERMINE PRE-PAD RETENTION

(Suspension was made up as follows: 250 liters of distilled water, 25 g. fiber, o.d. basis, 150 g. reagent-grade NaCl, 350 cc. TiO_2 slurry at 2.58 g./liter.)

Pad		$\underline{v}$, cm./sec.	Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$	$\underline{m}$, mg.
1D1	top	12.8	111.1	0.72	0.648	55.6
	-		95.9	0.75	0.783	150.1
	-		101.6	0.85	0.836	257.8
	septum		135.0	1.16	0.860	376.1
1D2	top	12.8	117.1	0.78	0.666	58.6
	-		84.6	0.64	0.756	159.4
	-		106.9	0.89	0.831	255.2
	septum		141.0	1.19	0.845	379.1
2D1	top	21.0	95.2	0.58	0.609	47.6
	-		84.9	0.59	0.695	137.7
	-		107.1	0.80	0.747	233.7
	septum		169.0	1.31	0.775	317.7
2D2	top	21.0	96.7	0.58	0.600	48.4
	-		82.0	0.59	0.720	137.7
	-		104.9	0.80	0.763	231.2
	septum		156.5	1.18	0.755	361.9
3D1	top	28.5	90.7	0.57	0.628	45.4
	-		92.1	0.57	0.619	136.8
	-		108.6	0.72	0.663	237.1
	septum		139.5	0.91	0.653	361.2
3D2	top	28.5	90.1	0.48	0.533	45.1
	-		76.7	0.47	0.613	128.5
	-		105.9	0.71	0.671	219.8
	septum		154.5	0.95	0.615	350.0
One-quart sheet mold:			92.3	0.22	0.239	
			97.8	0.23	0.235	
			86.9	0.17	0.196	
Two-quart sheet mold:			184.0	0.64	0.348	
			169.7	0.52	0.307	
			169.5	0.51	0.301	
One-liter settling:			73.8	0.20	0.271	
			92.0	0.33	0.359	
			102.8	0.31	0.302	
Two-liter settling:			189.5	0.64	0.338	
			192.7	0.73	0.379	
			201.3	0.69	0.343	

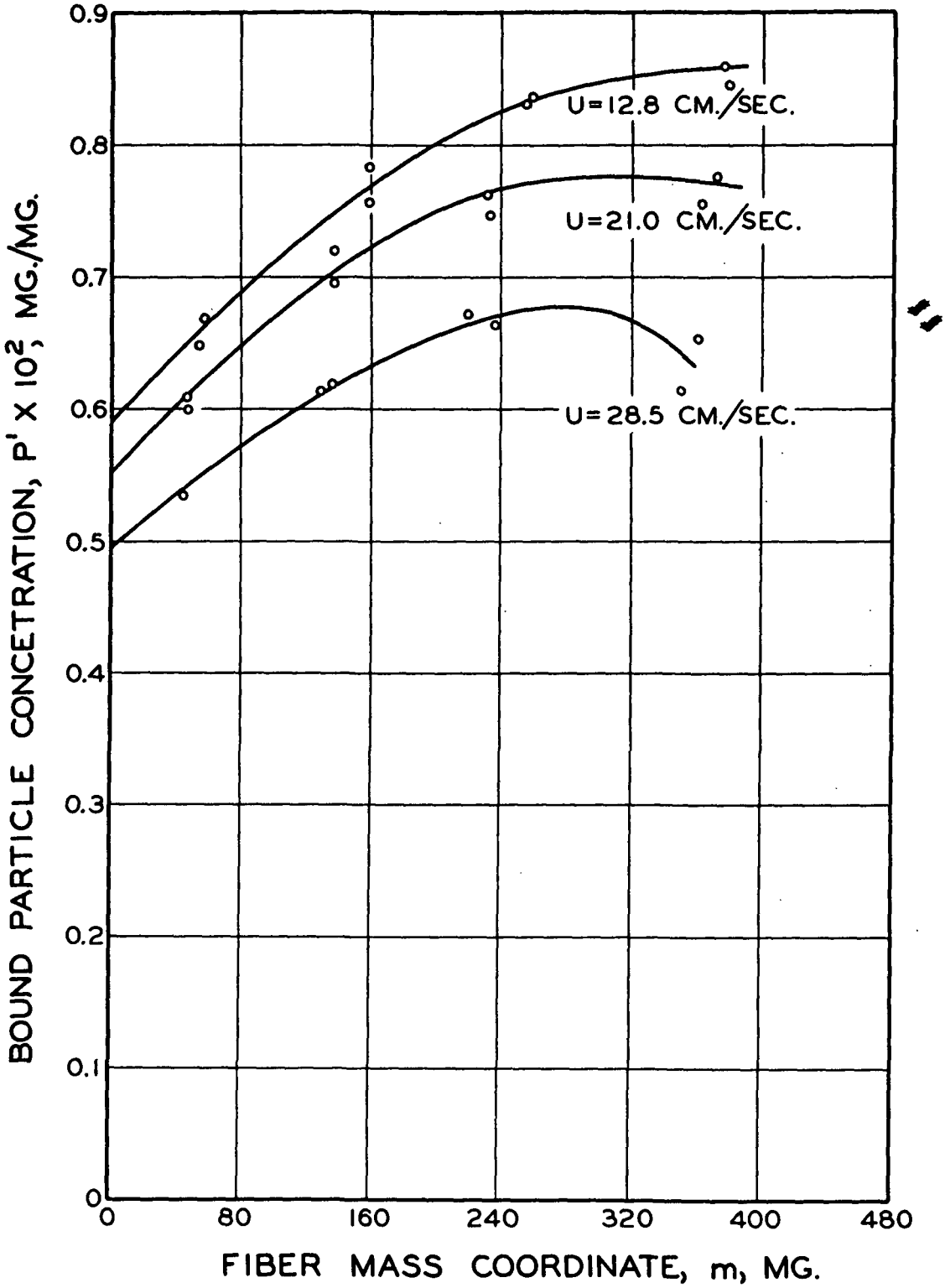

Figure 4. Particle Distribution Curves from Pre-Pad Retention Experiment

TABLE IV

COMPARISON OF VALUES OF PRE-PAD RETENTION MEASURED BY EXTRAPOLATION OF DISTRIBUTION CURVES, WITH VALUES MEASURED BY OTHER MEANS

Pre-Pad Retention, P_0', x 10^2, mg./mg.

Extrapolation of Distribution Curves	One-Liter Settling	Two-Liter Settling	Thin Pad one quart	Thin Pad, two quarts
0.590	0.271	0.338	0.239	0.348
0.551	0.359	0.379	0.235	0.307
0.495	0.302	0.343	0.196	0.301

is much higher in the region near the mat surface. If this is true, the distribution curves could be very steep in the region near the mat surface and come down to much lower values of the pre-pad retention. This would not be detectable with the few points used to draw the curves and make the extrapolation. A third possibility is that the pre-pad retention changes after the suspension leaves the tank. Then the added retention could occur during the process of filling the DDT.

WHOLE PAD DATA

The data presented so far have shown that the particle distributions were more complex than the predictions of the simplified theory, and had much more curvature than was expected. In addition, the values of the pre-pad retention determined by extrapolating the distribution curves to the mat surface were higher than those given by the other methods. It was suspected that a possible cause of these effects was a redistribution of the particles during the splitting process. In order to avoid the uncertainty introduced by the Beloit sheet splitter, a method of getting the desired data (the effect of the filtration velocity on the collection efficiency) without using the sheet splitter was tried.

In a steady-state retention process, theory indicates that the bound-particle concentration is a function only of the basis weight measured from the mat surface. In this case there is no difference if the distribution is found by splitting a mat or if it is found by forming sheets of different basis weights at the same flow and colloidal conditions, analyzing the whole mats, and constructing a distribution curve from the series of mats which were formed. This latter procedure was used in an attempt to obtain the desired data. A series of pads were formed from the same suspension at the same velocity. They were formed at different basis weights by stopping the piston at different stroke lengths. Each pad was analyzed for TiO_2 and fiber content, and a distribution curve was constructed from the aggregate of the data. A single curve could not be drawn because the total retention was found to be time dependent.

One experiment illustrating this problem is presented here. A suspension was made up in the tank at 0.01% consistency, 10^{-2} M salt concentration, and TiO_2 at 5% on the fiber. The TiO_2 was put into the tank a few minutes before the first pad was formed. The sequence in forming the pads was to begin with the thickest pads and then form smaller ones. After the smallest pad had been formed, two full pads were formed for splitting. The sequence was then continued, starting with the thinnest pad and increasing the thickness. A total of ten pads were formed, two of which were split. All pads were analyzed for TiO_2 and fiber content. The data are presented in Table V and are shown in Fig. 5. The numbers beside the points in Fig. 5 indicate the sequence in which they were formed. It is seen that the points do not fall on a single curve because the total retention increases with time. This is most likely caused by the pre-pad retention increasing with time. This time factor makes the aggregate distribution curve too flat when it is obtained by starting at high basis weights and going down, and too steep when obtained by starting at the low basis weights and going up. The two mats

TABLE V

RETENTION DATA FOR WHOLE AND SPLIT PADS

(Suspension was made up as follows: 250 liters distilled water, 25 g. fiber o.d. basis, 150 g. reagent-grade NaCl, 130 cc. TiO_2 slurry at 9.53 g. TiO_2 per liter.)

U_o = 12.1 cm./sec. for all pads.

Pad		Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$, mg./mg.	$\underline{m}$, mg.
1		450.9	6.10	1.353	225.5
2		236.9	2.78	1.173	118.5
3		119.9	1.27	1.062	60.0
4		71.6	0.75	1.047	35.8
5	top	112.8	1.40	1.245	56.4
	-	104.2	1.56	1.495	164.9
	-	113.6	1.89	1.664	273.8
	septum	124.6	2.18	1.750	392.9
6	top	92.3	1.19	1.290	46.2
	-	81.5	1.25	1.534	133.1
	-	114.5	2.02	1.765	231.1
	septum	160.6	3.03	1.888	368.6
7		77.2	0.99	1.282	38.6
8		122.7	1.77	1.453	61.4
9		230.8	3.80	1.656	115.4
10		438.1	8.34	1.904	219.1

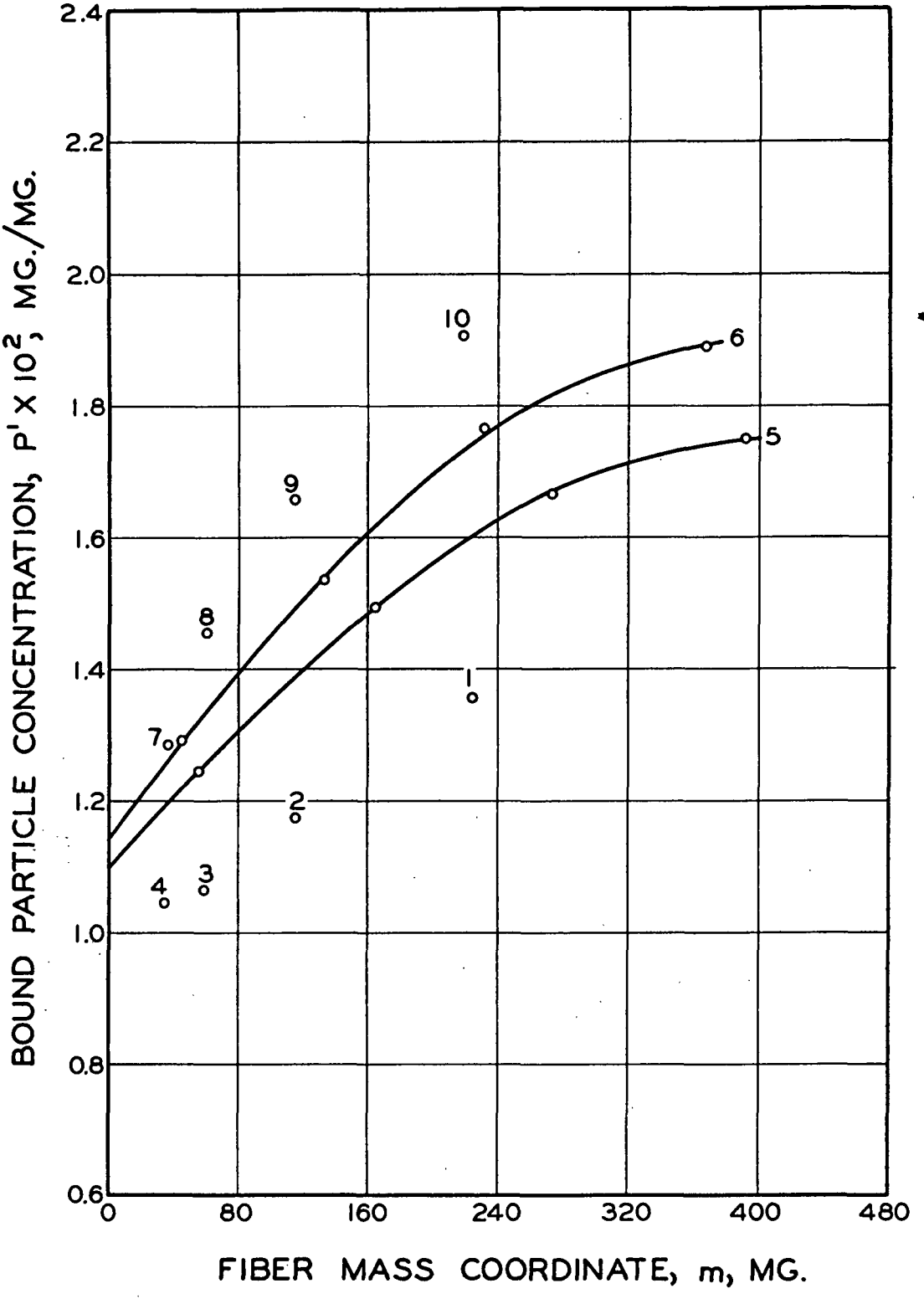

Figure 5. Particle Distribution Data Showing Effect of Forming Sequence

which were split were formed in the middle of the run and fall between the boundary mapped out by the other points. There is an interesting feature of the two mats which were split. One of these pads was quite wet when it went through the Beloit sheet splitter, while the other was about as dry as it could be and still split. Yet the distributions obtained for these two pads are very nearly the same. Thus, if the Beloit splitter does cause a redistribution of particles during the splitting process, the redistribution may not be very sensitive to the moisture content of the sheets in the range in which splitting is possible.

TIME EFFECTS

Since the method of obtaining distribution data by analyzing pads of different basis weights failed because the total retention increased with time, a means for making the method work seemed obvious. It appeared only necessary to determine how long it would take to reach steady-state retention in the tank, and then allow for this time after the TiO_2 had been put into the tank before making retention runs. It was assumed that the pre-pad retention would approach a steady-state value if given enough time. In order to determine this time, a series of experiments were performed in which complete pads were formed at constant hydrodynamic conditions at various times after the TiO_2 was admitted to the tank. These pads were formed at full piston stroke and the total amount of fiber and retained TiO_2 was measured for each pad. A total of four experiments were run, two experiments at each of two different NaCl concentrations. The procedure was simply to form a pad and analyze it and note the time at which the pad was formed.

The data for the runs at 10^{-2} M NaCl are given in Table VI, and the curves of total retention vs. time are shown in Fig. 6. The data for the runs at 10^{-3} M NaCl are given in Table VII, and the curves shown in Fig. 7. It may be noted in

TABLE VI

DATA SHOWING TOTAL RETENTION AS A FUNCTION OF TIME IN 10^{-2} M NaCl

(Suspension was made up as follows: 250 liters distilled water, 25 g. fiber o.d. basis, 150 g. reagent-grade NaCl, 130 cc. of TiO_2 slurry at 9.53 g. TiO_2 per liter added at time = 0.)

All pads formed at full piston stroke at a velocity of 20.9 cm./sec.

Time, min.	Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$, mg./mg.
3	457.7	2.94	0.643
11	449.8	4.77	1.061
23	447.0	6.67	1.493
31	448.3	7.84	1.750
61	448.5	9.87	2.202
90	442.3	10.28	2.324
118	435.2	10.01	2.304
184	434.4	9.35	2.152
240	421.6	8.27	1.963
300	422.8	7.70	1.821
358	424.6	7.08	1.668
413	413.8	6.53	1.578
1402	411.5	4.77	1.160
12	440.8	4.375	0.993
18	439.2	4.375	0.996
29	436.8	5.245	1.201
59	433.0	7.55	1.754
87	433.6	8.54	1.970
121	427.4	9.15	2.141
150	429.5	9.43	2.196
218	427.4	9.28	2.171
270	415.2	8.85	2.132
332	412.1	8.26	2.004
389	405.4	7.55	1.862
436	401.6	7.13	1.775

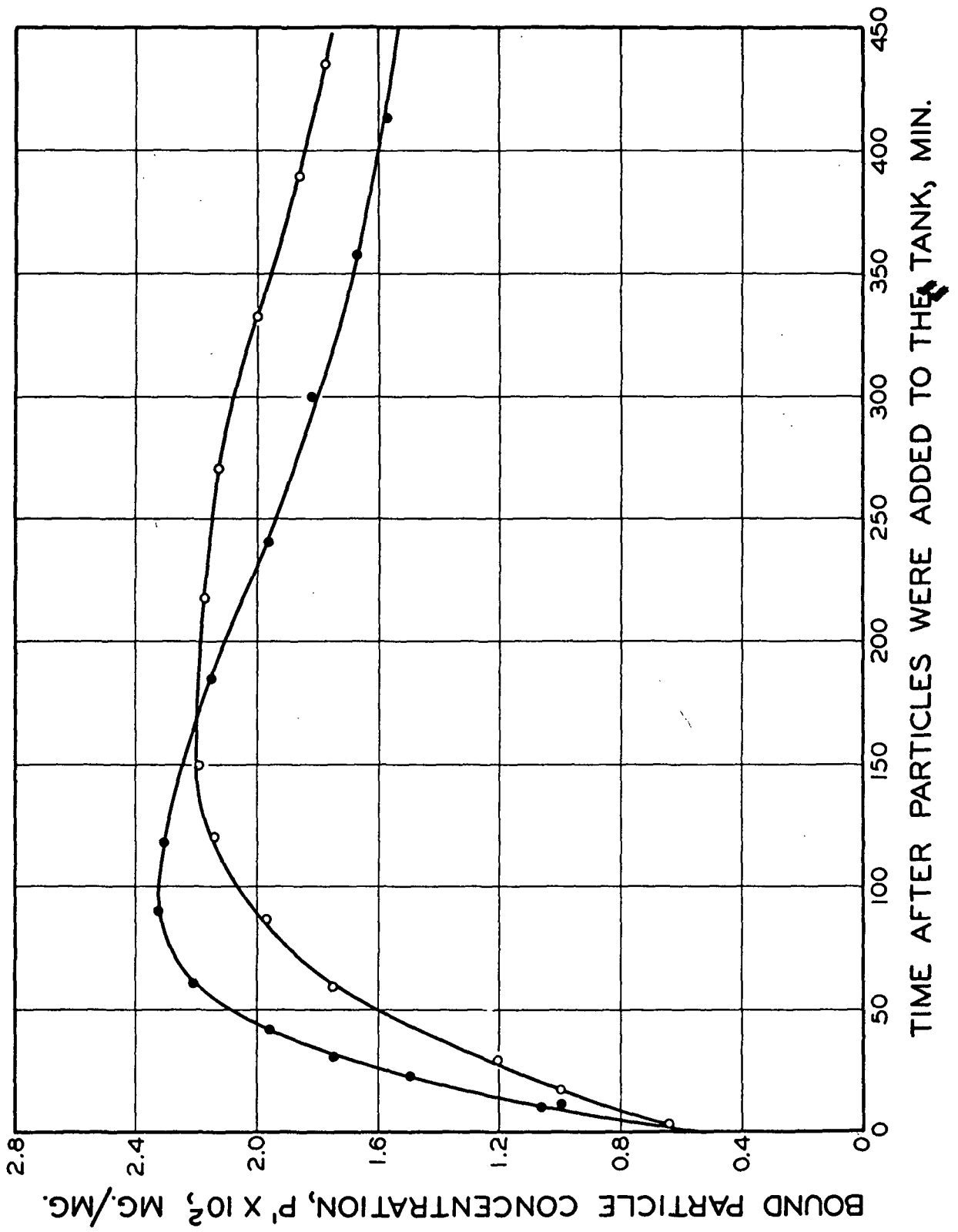

Figure 6. Effect of Time on Total Retention at 10^{-2} M NaCl Concentration

TABLE VII

DATA SHOWING TOTAL RETENTION AS A FUNCTION OF TIME IN 10^{-3} M NaCl

(Suspension was made up as follows: 250 liters distilled water, 25 g. fiber o.d. basis, 15 g. reagent-grade NaCl, 130 cc. of TiO_2 slurry at 9.53 g./liter, added at time = 0.)

All pads formed at full piston stroke and a velocity of 20.9 cm./sec.

Time, min.	Fiber, mg.	TiO_2, mg.	P' x 10^2, mg./mg.
6	444.2	1.563	0.352
15	450.2	1.480	0.329
30	441.8	1.558	0.353
60	456.0	1.900	0.417
90	439.6	1.970	0.448
118	436.2	1.933	0.443
145	435.2	1.970	0.453
237	425.1	1.933	0.455
336	425.4	2.030	0.477
440	415.2	2.018	0.486
9	433.5	1.612	0.372
18	438.9	1.211	0.276
29	436.7	1.273	0.292
58	436.2	1.621	0.372
88	438.1	1.845	0.421
119	433.6	1.858	0.429
147	428.5	1.858	0.434
220	422.2	2.065	0.489
254	483.3	2.137	0.442
299	416.6	2.01	0.482
347	409.7	1.95	0.476
387	414.6	2.04	0.492

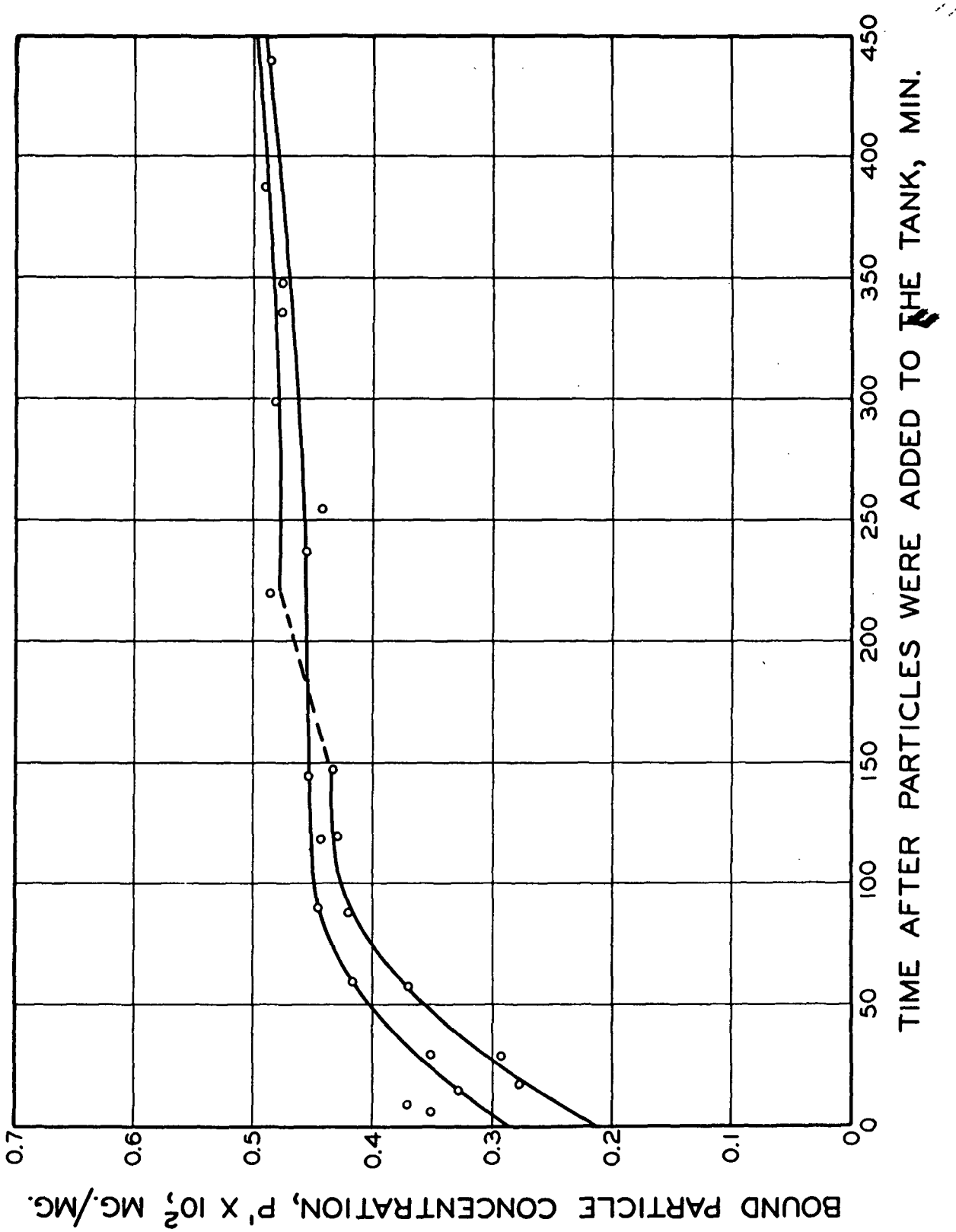

Figure 7. Effect of Time on Total Retention at 10^{-3} M NaCl Concentration

the tables that the total basis weight of the mats decreases slightly as time proceeds. This is due to a small classification and settling effect in the tank. This effect is at least partially compensated for in the curves, which are based on particle concentration. The curves are quite interesting. At an NaCl concentration of 10^{-2} M, the retention increases rapidly with time, passes through a maximum, and then decreases at a slow rate. The existence of a maximum seemed strange at first, and is apparently due to flocculation of the TiO_2 in the tank. The evidence for this was the visual observation that the slurry being fed to the DDT from the tank became less opaque as time proceeded. Since the retention of TiO_2 was not increasing with time at this stage, the reduced opacity was not due to increased retention, and must have been due to an increase in the particle size. The visual evidence of reduced opacity combined with the strange nature of the retention versus time curves seems to indicate particle flocculation. This introduces another complexity into the retention process--the possibility that the particles undergo flocculation at the same time that the retention process is going on. In order to have enough retention to make accurate measurements it is necessary to have colloidal conditions favorable to retention. However, these conditions are also favorable for the flocculation of the fiber and the TiO_2. This is because the physicochemical nature of the retention process is similar to the physicochemical processes that govern the flocculation of fibers and TiO_2. This is shown by the two experiments at 10^{-3} M NaCl. Here the total retention did not exhibit a maximum in time. There was no visual indication of reduced opacity of the suspension either. In the more dilute salt suspension, the retention appears to rise and reach a steady state in agreement with what was expected. A comparison between the experiments at the two levels of salt concentration shows that although the complicating effects of particle flocculation are minimized in the case of the more dilute salt concentration, the total retention is reduced by about a factor of 5.

The complicating effects of using high salt concentrations can be eliminated, but at the expense of reducing the amount of material retained to a level where it becomes difficult to detect it quantitatively with the desired degree of accuracy.

The reproducibility between duplicate runs is not very good. The forming conditions were reproduced quite accurately, so the differences between the runs are apparently ascribable to small differences in the colloidal conditions in making up new batches of suspension for use in the duplicate runs. This shows the dominance of the colloidal aspects of the retention process and indicates why it is difficult to repeat results with the accuracy which is required for a complete understanding of the hydrodynamic aspects of the retention process.

These total retention data are difficult to analyze in detail because they include retention from two different mechanisms. Both pre-pad retention which is governed by turbulent diffusion in the tank, and retention during pad formation are present. It is impossible to say precisely for the case where total retention goes through a maximum with time whether the effect is due to changes in the pre-pad retention or to changes in retention during formation. It would seem to be most probable that the pre-pad retention reaches a steady state and that the decrease in total retention is due to a decrease in retention during formation because of the larger particles, but this is not definite. If there is a decrease in the pre-pad retention, the particles must detach from the fiber surface, flocculate, and then be less likely to be reattached. The indications of particle flocculation point up some aspects of the retention process which are extremely important, but which we had not given sufficient attention. An awareness of this factor and the experiments which are required to cope with it should ultimately lead to a much greater understanding of the processes which underlie the retention of small particles.

EVALUATION OF THE SPLITTING PROCESS

The final experiment on the DDT was designed to determine whether or not the use of the Beloit sheet splitter caused redistribution of particles. For this experiment the consistency of the suspension was increased to 0.03% so that pads with a basis weight of 300 g./m.^{2} could be formed. The salt concentration was reduced to 10^{-4} M in order to minimize fiber and particle flocculation effects. A total of twelve pads were formed at the same velocity. The basis weights were varied by controlling the length of stroke of the piston. All pads were formed at a low velocity so as not to exceed the pressure limitations of the DDT. Four 100-g./m.^{2} pads, four 200-g./m.^{2} pads, and four 300-g./m.^{2} pads were formed. At each basis weight, different combinations of the Beloit splitter and hand splitting with a dissecting needle were used. Table VIII gives the suspension furnish and the method of splitting the sheets. It should be mentioned that hand splitting the 100-g./m.^{2} sheets was very difficult, particularly when they were split into quarters.

The retention data obtained are presented in Table IX and plotted in Fig. 8. These data indicate that there is a subtle effect due to the Beloit splitter. The Beloit splitter seems to cause small shifts in the distribution curves. This is seen most clearly with the 200 and 300-g./m.^{2} pads. Of the 200-g./m.^{2} pads, those that went through the sheet splitter follow the same general trend as the hand-split pads, but with greater variation within the trend. The pad which was split in half by hand and then split further on the Beloit splitter shows two concave-upward curves joined near the middle. The connecting position corresponds to the hand split. The two pads which were entirely hand split have distributions which are very nearly linear with practically the same slope for both pads. The 300-g./m.^{2} pads do not show the effects of the Beloit splitter as

TABLE VIII

CONDITIONS FOR EXPERIMENT TO DETERMINE EFFECT OF SPLITTING

(Suspension was made up as follows: 250 liters distilled water, 75 g. fiber o.d. basis, 1.5 g. reagent-grade NaCl, 400 cc. TiO_2 slurry at 9.94 g./liter)

Forming velocity was 8.5 cm./sec. for all pads.

1	1/3 piston stroke; split entirely on the Beloit splitter
2	1/3 piston stroke; split entirely on the Beloit splitter
3	1/3 piston stroke; split in half by hand and finished on Beloit splitter
4	1/3 piston stroke; split entirely by hand
5	2/3 piston stroke; split entirely on the Beloit splitter
6	2/3 piston stroke; split in half by hand and finished on Beloit splitter
7	2/3 piston stroke; split entirely by hand
8	2/3 piston stroke; split entirely by hand
9	full piston stroke; split entirely on the Beloit splitter
10	full piston stroke; split in half by hand and finished on Beloit splitter
11	full piston stroke; split entirely by hand
12	full piston stroke; split entirely by hand

TABLE IX

DISTRIBUTION DATA FROM SHEET SPLITTING EXPERIMENT

Pad		Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$, mg./mg.	$\underline{m}$, mg.
1	top	117.7	0.189	0.161	58.9
	-	102.8	0.215	0.209	169.1
	-	114.3	0.290	0.254	277.7
1	septum	125.8	0.364	0.290	397.7
2	top	119.6	0.199	0.167	59.8
	-	103.4	0.199	0.192	171.3
	-	120.2	0.285	0.237	283.1
2	septum	132.7	0.342	0.258	409.6
3	top	89.0	0.129	0.145	44.5
	-	84.6	0.163	0.193	131.3
	-	146.8	0.359	0.245	247.0
3	septum	140.9	0.385	0.273	390.9
4	top	86.7	0.146	0.168	43.4
	-	165.4	0.337	0.204	169.4
	-	97.7	0.354	0.362	301.0
4	septum	89.9	0.225	0.251	394.8
5	top	86.7	0.146	0.168	43.4
	-	86.4	0.168	0.195	129.9
	-	79.4	0.182	0.229	212.8
	-	80.4	0.225	0.280	292.7
	-	133.5	0.436	0.327	399.7
	-	130.4	0.505	0.387	531.6
	-	133.8	0.620	0.463	663.7
5	septum	144.1	0.733	0.509	802.7
6	top	89.7	0.158	0.176	44.9
	-	92.2	0.189	0.205	135.8
	-	88.5	0.211	0.238	226.2
	-	89.8	0.263	0.293	315.3
	-	182.4	0.654	0.358	451.4
	-	146.4	0.620	0.424	615.8
	-	96.9	0.467	0.482	737.5
6	septum	107.4	0.526	0.490	839.6
7	top	197.7	0.342	0.173	98.9
	-	209.6	0.560	0.267	302.5
	-	172.9	0.620	0.359	493.8
	-	143.2	0.632	0.441	651.8
7	septum	176.3	0.872	0.495	811.6

TABLE IX (Contd.)

DISTRIBUTION DATA FROM SHEET SPLITTING EXPERIMENT

Pad		Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$, mg./mg.	$\underline{m}$, mg.
8	top	143.3	0.278	0.194	71.7
	-	240.6	0.682	0.284	263.6
	-	265.3	1.118	0.422	516.6
	-	124.4	0.654	0.525	711.4
8	septum	96.5	0.522	0.541	821.9
9	top	95.4	0.189	0.198	47.7
	-	86.7	0.210	0.242	138.8
	-	118.9	0.328	0.276	241.6
	-	86.4	0.299	0.347	344.2
	-	85.8	0.316	0.369	430.3
	-	114.3	0.462	0.403	530.4
	-	166.3	0.720	0.432	670.7
	-	121.8	0.687	0.565	814.7
	-	169.7	1.071	0.633	960.5
	-	107.6	0.766	0.712	1099.1
9	septum	136.5	0.958	0.702	1221.2
10	top	125.0	0.232	0.186	62.5
	-	96.5	0.220	0.228	173.3
	-	203.1	0.650	0.320	323.1
	-	216.9	0.929	0.428	533.1
	-	156.5	0.767	0.490	719.8
	-	130.7	0.795	0.609	863.4
10	septum	349.8	2.528	0.724	1103.6
11	top	225.1	0.500	0.222	112.6
	-	310.5	1.153	0.372	380.4
	-	54.5	0.268	0.492	562.9
	-	209.9	1.084	0.517	695.1
	-	229.3	1.460	0.638	914.7
	-	122.8	0.905	0.737	1090.7
11	septum	108.8	0.745	0.685	1206.5
12	top	127.7	0.232	0.182	63.9
	-	181.4	0.436	0.240	218.4
	-	180.6	0.589	0.326	399.4
	-	145.7	0.589	0.404	562.6
	-	240.6	1.203	0.501	755.7
	-	137.6	0.816	0.593	944.8
	-	188.3	1.328	0.705	1107.8
12	septum	94.3	0.610	0.648	1249.1

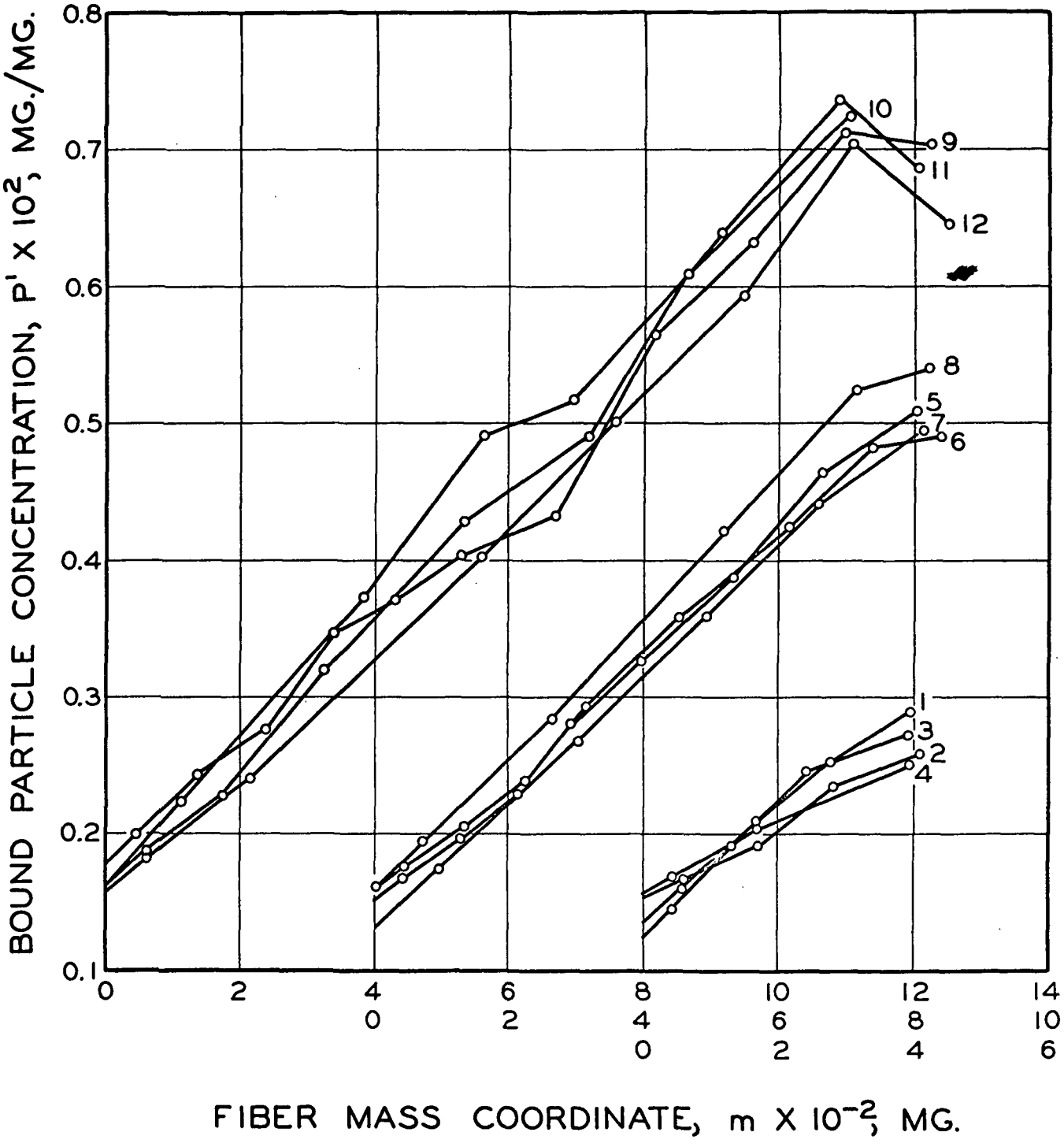

Figure 8. Particle Distribution Curves from Experiment to Evaluate the Beloit Sheet Splitter

clearly. The all-Beloit-split pad is the least uniform. The half-hand-split pad is not too bad, and again seems to consist of two distinct curves. The hand-split-only pads have distribution curves which are not as uniform as those obtained for the 200-g./m.^{2} pads. The reason for this is that there was some difficulty in hand splitting the largest pads, particularly into the smallest fractions. There was a small amount of nonuniformity across the sheet that interfered with the progress of splits once they were started. This was due to a small amount of fiber flocculation and the presence of the bend in the DDT so that as fibers settled they introduced a consistency gradient across the lateral dimension which caused a nonuniformity in the formation. The conditions for forming the 300-g./m.^{2} pads were about the worst that could be encountered on the DDT. The consistency was three times higher than usual and the pads were formed at about the lowest velocity that could be reliably obtained. The higher consistency increased the tendency to form flocs and the low velocity allowed the flocs a greater time to form and settle as they flowed around the bend. The net result was some nonuniformity of the 300-g. pads which affected the ability to split them. It does not seem likely that this nonuniformity was significant in the other experiments since the conditions for the 300-g./m.^{2} pads represented an extreme and the amount of nonuniformity that did occur was not very marked, merely enough to prevent splitting cleanly across fiber layers. It is difficult to say much about the 100-g./m.^{2} pads because these were so difficult to hand split. The distribution curves for these pads agree quite well with the curves for the higher basis weights. There is obviously one faulty datum point in the hand-split case.

It is of interest that there seems to be a tendency for a decrease in bound-particle concentration at the septum end. This was present in some of the other retention data and is most prevalent here in the 300-g./m.^{2} data. A slight

trend toward the same thing can be detected in the 200-g./m.^{2} data. This was observed in hand-split pads and so cannot be considered as a splitting effect. The significance of a decrease will be discussed in more detail later on. The general conclusion from the experiment was that the Beloit splitter can cause small changes in the distribution of bound particles in the mat and that these changes can be significant when studying details of hydrodynamic effects.

WEB FORMER EXPERIMENTS

In addition to the work on the DDT, some retention experiments were performed on the Web Former. In the original plan, the retention behavior on the Web Former was the primary goal of the program and the experiments on the DDT were to provide the necessary quantitative data for analyzing the results of the Web Former experiments. The advantage of the Web Former is that it approximates more closely the processes which occur on an actual paper machine. The disadvantage of the Web Former is that it is more difficult to control experimental variables. The results of the DDT experiments indicated that the hydrodynamic aspects of the retention process were more complex and more important than we had thought. Thus, the use of the Web Former for a quantitative study of the retention process is premature. However, some preliminary experiments were made on the Web Former in order to become familiar with the type of retention data that could be obtained on it.

A large plastic swimming pool with a capacity of 1000 gallons was obtained for use as a stock tank in the retention experiments. In order to keep the suspension in the pool from settling out, two Lightnin' mixers, a pump, and an air bubbler in the bottom of the pool were used to keep the contents in a state of turbulent mixing. The suspension for the Web Former runs was quite different from

that used in the DDT experiments. The consistency of the stock was 0.05%, much higher than that on the DDT. This was required by drainage limitations of the Web Former. In the initial trials on the Web Former, when salt was added to the suspension the fiber flocculated badly and the formation of the sheets was poor. This could not be tolerated for the retention experiments. By trial and error it was found that the best method of running was to keep the consistency as low as possible, omit the salt entirely, and increase the TiO_2 concentration to 30% on the fiber to make up for the reduced retention. Under these conditions it was possible to get acceptable formation and still retain enough particles so that they could be measured.

The first experiment run on the Web Former was made to determine whether or not there was time variation similar to that encountered with the DDT work. The Web Former was adjusted to form a sheet of about 50 g./m.^{2}. Samples were taken periodically off the wet end, and the time at which the samples were taken was noted. The samples were placed in crucibles and analyzed in the usual manner. The data are presented in Table X, and the results are plotted in Fig. 9. There does not appear to be a rise time in the retention on the Web Former. Because of the scatter of the data, it is difficult to determine whether long-term time effects exist. The absence of time effects is probably due to two causes: The lack of salt in the Web Former runs, which was necessary to prevent fiber flocculation, also acted to prevent flocculation of the TiO_2. The second factor was the very violent mixing, particularly with the air blower, which helped to reduce the time constant for retention in the stock chest. These two factors apparently prevented the pronounced time dependency which was found in the DDT work.

The effect that introducing air into the tank in order to disperse the suspension might have on the retention was ignored. Another problem was that some

TABLE X

DATA SHOWING TIME DEPENDENCE OF RETENTION ON WEB FORMER

(The suspension was made up as follows: 4000 liters of city water, 2000 g. fiber, o.d. basis, single pass classified, 650 cc. TiO_2 slurry at 926 g./liter, 600 g. TiO_2, added at time = 0.)

Time, min.	Fiber, mg.	TiO_2, mg.	$\underline{P}'$ x 10^2, mg./mg.	Pressure Drop, cm. H_2O	Basis Weight, g./m.^{2}	Wire Speed, ft./min.
2	485.1	2.935	0.605	--	48	--
5	414.9	2.65	0.639	15	48	--
10	627.5	4.55	0.725	--	47	7.51
15	714.1	4.805	0.673	15	45	--
20	590.5	3.59	0.608	15	45	7.75
25	566.5	3.603	0.636	20	46	7.41
30	701.4	4.79	0.679	15	46	--
41	681.5	4.649	0.681	15	46	7.44
51	687.4	4.649	0.676	15	47	7.44
61	680.0	4.649	0.683	15	46	7.44
71	684.2	4.649	0.679	15	46	7.44
81	684.2	4.649	0.679	15	46	7.44

Note: After 71 minutes, the headbox was shut off except for the time needed to make samples.

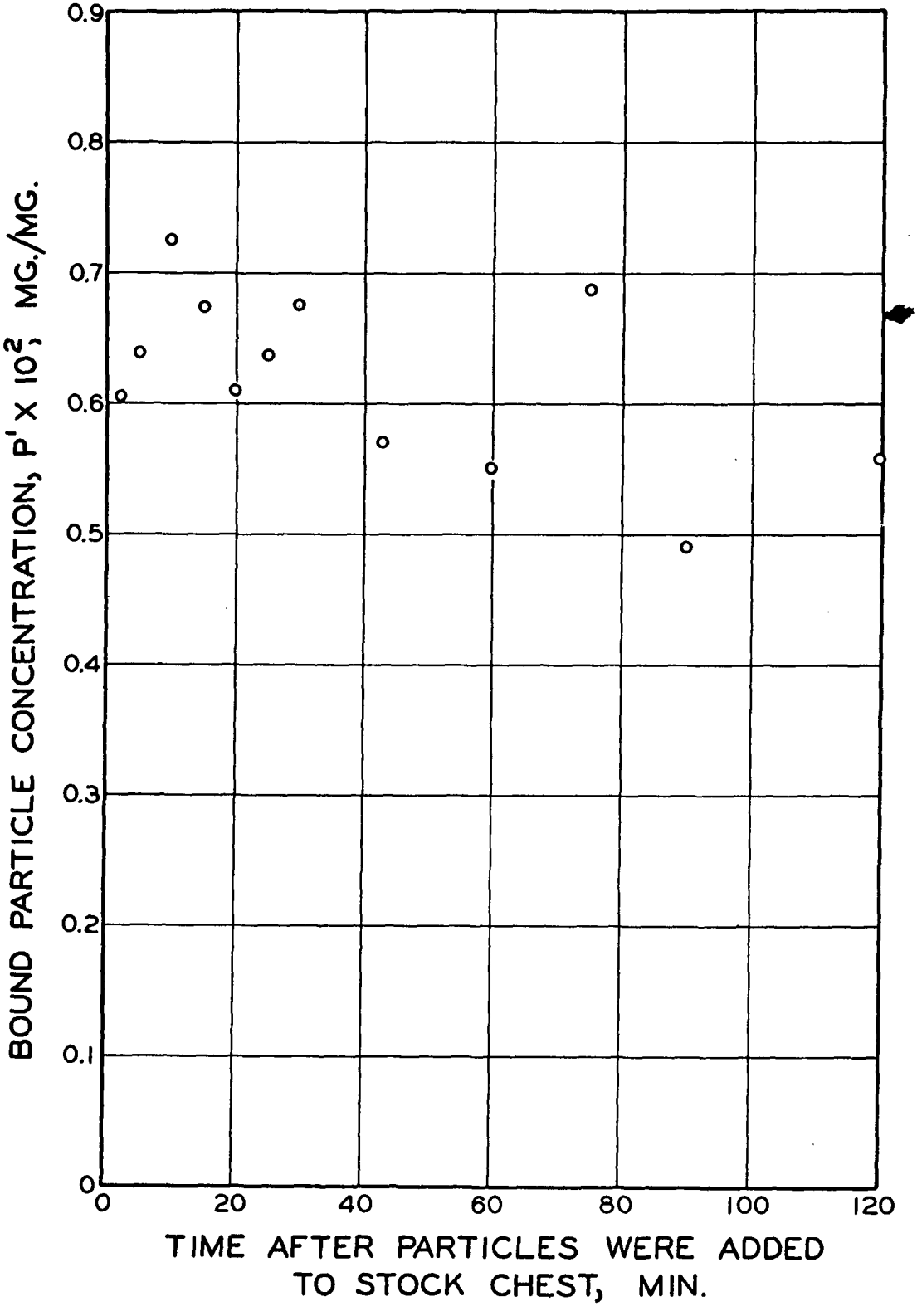

Figure 9. Effect of Time on Total Retention on the Web Former

air was pulled through the sheet after it was formed. This occurred because the Web Former is a suction-forming device, and in order to remove the water from the slurry and consolidate the web it is necessary to remove the free water before the mat leaves the forming zone. Since the forming length on the Web Former is not a perfectly straight line, it is necessary to have a dry line somewhere ahead of the end of the forming zone, and hence pull air through the sheet. Earlier work at the Institute has shown that pulling air through a sheet can cause removal of particles. This problem was recognized when using the Web Former, but no steps were taken to avoid it or to try to determine the magnitude of the loss, if any.

The second experiment on the Web Former illustrates the type of data which can be expected. In this experiment, the effect of basis weight and pressure drop over the forming zone on retention was explored by varying the forming conditions on the machine. The data are given in Table XI. In the first part of the experiment, the basis weight of the sheet was increased in increments from about 10 to about 50 g./m.^{2}, with the pressure drop across the forming zone held constant near 12.0 cm. of water. In order to obtain higher basis weights, the pressure drop had to be increased in order to prevent over-running. At each forming condition, a sample was scraped from the wire in the wet state before it had had contact with the felt, and another sample was taken off the drier drum. The object was to determine whether or not there was significant transfer of particles to or from the pickup felt and on the drier drum. After a sheet of basis weight of about 90 g./m.^{2} was obtained, the pressure drop was increased in increments at constant basis weight. No splitting was done on the Web Former samples; they were all analyzed as a whole.

TABLE XI

PRELIMINARY RETENTION DATA ON IPC WEB FORMER

Sample		Fiber, mg.	TiO_2, mg.	$\underline{P}' \times 10^2$, mg./mg.	Pressure Drop, cm. H_2O	Basis Weight, $g./m.^2$	Wire Speed, ft./min.
1	wet	784.0	1.88	0.240	11.5	12.5	[illegible]
1	dry	256.0	0.523	0.204	11.5	12.5	30
2	wet	442.8	0.80	0.181	11.5	10.7	36.5
2	dry	732.6	1.235	0.169	11.5	10.7	36.5
3	wet	479.1	1.50	0.313	10.5	20.0	18.9
3	dry	260.1	0.725	0.279	10.5	20.0	18.9
4	wet	539.6	2.54	0.471	11.5	30.5	12.6
4	dry	215.8	0.918	0.425	11.5	30.5	12.6
5	wet	516.4	3.36	0.651	11.0	42.5	9.8
5	dry	263.3	1.436	0.545	11.0	42.5	9.8
6	wet	542.1	4.12	0.760	11.7	48.2	7.82
6	dry	339.5	2.233	0.658	11.7	48.2	7.82
7	wet	570.4	5.115	0.897	17.5	62.0	6.0
7	dry	379.0	3.70	0.976	17.5	62.0	6.0
8	wet	436.7	4.325	0.990	20.0	75.0	5.22
8	dry	358.1	3.415	0.954	20.0	75.0	5.22
9	wet	475.8	5.64	1.185	22.0	91.5	4.4
9	dry	451.4	5.53	1.225	22.0	91.5	4.4
10	wet	754.1	8.22	1.090	30.0	91.5	4.4
11	wet	561.0	5.49	0.979	40.0	91.5	4.4
12	wet	365.0	2.895	0.793	50.0	91.5	4.4
13	wet	559.3	4.12	0.737	53.0	91.5	4.4
14	wet	326.0	0.478	0.147	14.0	12.0	32
15	wet	452.5	0.925	0.204	11.0	12.0	32

The results of the Web Former experiments are presented in Fig. 10 and 11. Figure 10 shows the data as the basis weight was varied. As the basis weight increased at constant pressure drop, the average particle concentration increased in an almost linear manner, with a slight amount of upward curvature. The concentration in the wet samples was always higher than that in the dry samples in this region. This would indicate transfer of particles from the wet mat to the pickup felt. A linear variation of particle concentration with basis weight would indicate a constant collection efficiency. The data indicate that this may be a reasonable approximation. The curve extrapolates back to a very low particle concentration, which indicates that in this experiment at least, pre-pad retention is not the dominant mode of the retention of small particles. Most of the retention must have occurred during sheet formation. The slight amount of upward curvature that is evident is in agreement with the idea that as the basis weight is increased at constant pressure drop, the average velocity during mat formation will decrease, which should lead to a higher average collection efficiency. This would cause greater retention for the thicker sheets and hence an upward curvature as the basis weight increases. A sharp break occurs in the curve when the pressure drop is increased. The pressure drop across the sheet has a strong effect on the retention. This is due to at least two factors: As the pressure drop increases, the velocity during formation increases, which should lower the retention. There is also greater opportunity for loss of particles due to air being pulled through the sheet at the higher pressure drops. Interestingly enough, there is a trend toward a reversal of the wet and dry samples for these high basis weights at the higher pressure drops. The reasons for this are not obvious.

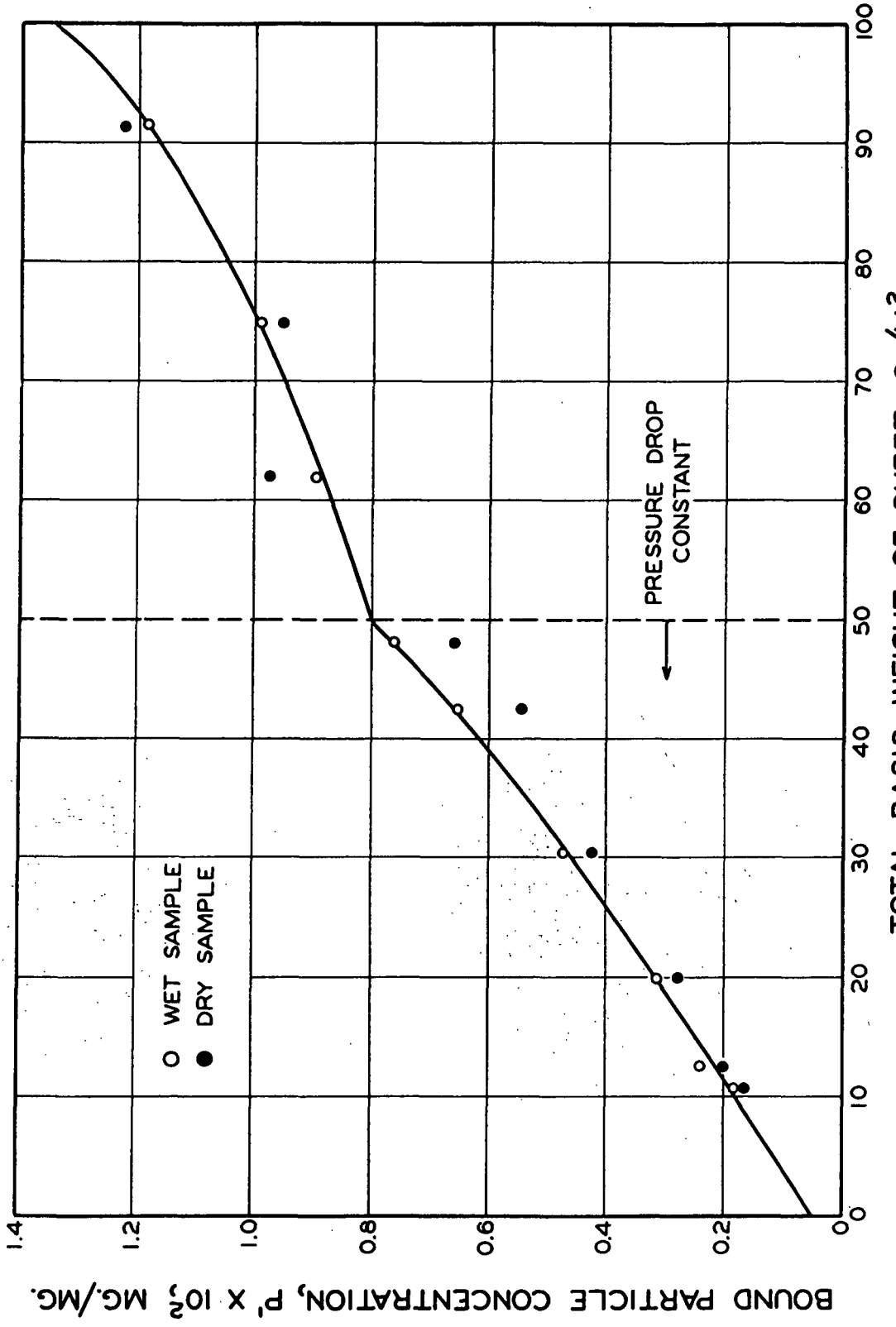

Figure 10. Variation of Bound-Particle Concentration with Basis Weight During Retention Experiment on the Web Former

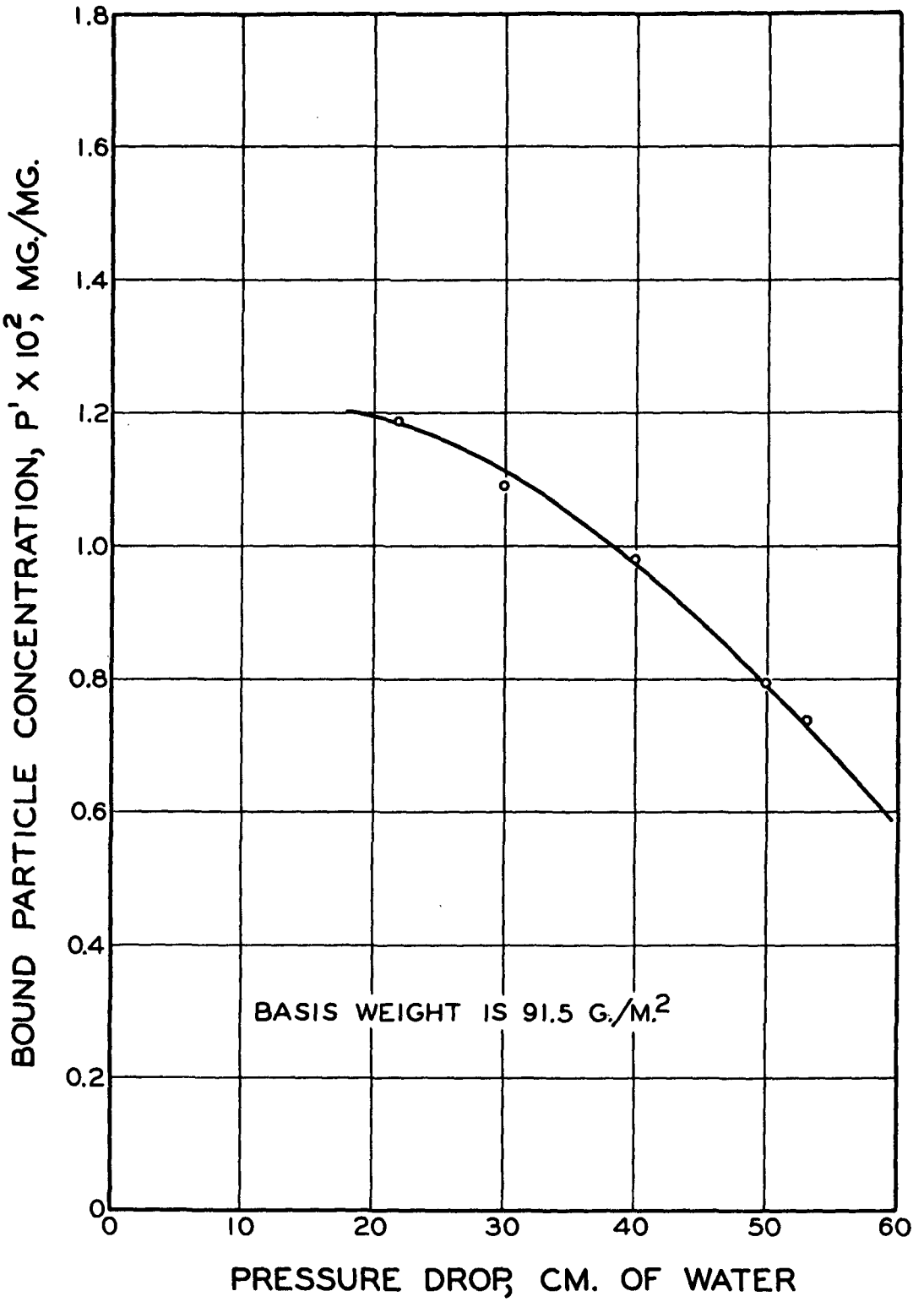

Figure 11. Effect of Pressure Drop on the Total Retention on the Web Former

Figure 11 shows the effect of increasing the pressure drop at a constant basis weight. The retention drops off rapidly as the pressure drop is increased. This is probably due to the two reasons discussed above. In any event, the retention is a strong function of the pressure drop on the Web Former, and probably on any kind of suction-forming device. These data must be considered of a preliminary nature, and are not directly useful for a quantitative understanding of the retention problem. It is important to point out, however, that all of the trends which were observed are in agreement with what would be expected from theoretical considerations. In this respect, the results of the experiments on the Web Former substantiate the other retention work.

DISCUSSION OF RESULTS

In this section the data which have been presented previously will be discussed. The discussion will go into detail concerning the significance of the findings that have been made, assess them in terms of their bearing on the study of particle retention in the sheet-forming project, and indicate some additional experiments which will be performed in the next phase of the project.

CURVED PARTICLE DISTRIBUTIONS

The first data to be considered are those on the effect of filtrate velocity and particle concentration on the distribution of bound particles in a mat formed by a constant-rate filtration process. In the experiments in which the filtrate velocity was varied, linear plots of bound-particle concentration versus the basis weight coordinate were not obtained. The distributions are curved and this curvature is an important indication of additional hydrodynamic effects. The general shape of all of the curves is fairly steep in the region near the mat surface, becoming flatter as one goes away from the mat surface. The distributions have a tendency to level out and possibly go through a maximum and begin to decrease. As the velocity is increased, the curves become less steep in the region near the mat surface (the slope of the curves near $\underline{w} = 0$ decreases as the velocity is increased) and level off at lower values of the bound-particle concentration.

The fact that this type of curvature was observed means that the collection efficiency was not constant throughout the mat, even though the velocity was constant. There are many possible explanations for this type of behavior, and in order to understand them it will be necessary to consider the retention equations in detail. Before doing this, it must be shown that the curvature in the present

data is not the same as the saturation phenomenon which was found in the earlier study. The strongest indication that it is not a saturation effect is the data in which the particle concentration was varied. All of the pads formed in this experiment showed the curved distributions and the tendency to level out. However, the total amount retained was directly proportional to the concentration of particles, so that all of the curves fell together when plotted relative to the total particles available. Thus, the leveling occurred at the same fraction of particles retained rather than at any absolute level of retention. This type of behavior would argue against a saturation type of phenomenon, in the sense of saturation being the ability of the fiber to retain only a certain limited amount of particles under given conditions. It could be argued that saturation represents some sort of equilibrium between free particles and bound particles. However, under the dynamic conditions which occur during pad formation, it is doubtful whether an equilibrium of this type could be set up. Since the rate of retention is theoretically proportional to the free-particle concentration, the most likely explanation of those data is a change in the retention rate due to factors other than particle concentration. Thus, it seems reasonable to look for complications other than saturation to explain the large deviations from idealized behavior in the present data. The complicated distributions which were found in the present study were not observed in the earlier work. This is because this work was done at significantly higher velocities than the older retention work. Examination of the curves in Fig. 1 shows that the effects become more pronounced as the velocity of pad formation is increased. It is probable that the earlier retention experiments were performed at velocities so low ($\approx$ 1 cm./sec.) that the effects were not present. It does not appear as though the present data are in contradiction to the earlier work on retention. These data seem to indicate additional effects which are due to the extended region of interest. Another

factor that distinguishes this work from the earlier work is that present experiments were made with relatively thin pads. This could also be responsible for the more complex behavior which has been found.

Several different explanations for the curved distributions are possible and will be discussed. The discussion will be of a qualitative nature only, giving some possible physical reasons for the observed behavior. It is felt that the data are not sufficiently accurate or precise for quantitative analysis. The qualitative arguments can provide an explanation for the behavior, suggest possible mathematical methods for treating the effects, and indicate some experiments which can be performed which would affirm or disprove some of the explanations.

The general form of the bound-particle retention equation is as follows:

$$-\rho_w s U_o \frac{\partial P'}{\partial w} = \frac{\partial P'}{\partial t} - \rho_w S \left[U_o - \frac{U_f}{(1 - \epsilon)} \right] EP \qquad (2) .$$

For the moment, the complicating effect of considering the free-particle equation in conjunction with it will be ignored. This is a legitimate procedure when the amount of particles retained during the filtration process is a small fraction (less than 10-20%) of the total free particles available. In solving Equation (2) for the ideal case, it is assumed that the collection efficiency is constant, that the boundary conditions are time independent, and that U_f is negligible compared to U_o . Then the time dependence does not enter and the equation can be solved. The resulting distribution is a linear increase in the bound-particle concentration with w . Going to the more general case, if the boundary conditions are not changing in time, then complicating effects must enter because of changes in the collection efficiency. Once the collection efficiency is allowed to be variable, there are three cases which can occur. The collection efficiency can be a

function of w alone, a function of t alone, or a function of both w and t. Of these three cases, only the first is amenable to immediate treatment. In this discussion, we are considering filtration from a low consistency, so that compressibility effects are limited to a very small region close to the mat surface and U_f is negligible.

If the collection efficiency is taken to be a function only of w, the time derivative term can still be neglected and the equation immediately solved. In this case the slope of the P' vs. w curve is directly proportional to the collection efficiency. Thus, one way of interpreting the curved distributions is to consider the curvature as directly related to changes in the collection efficiency with w. It is to be emphasized that the interpretation of the slope of the distribution curve as the collection efficiency can be done validly only when $E = E(w)$, and is not a function of time. If the collection efficiency is a function of time also, then the slope does not give the collection efficiency directly, but some sort of time average of E at each value of w. It would be desirable to interpret the slope of the distribution curve as E. In order to do this, it is necessary to find some quantity that E is reasonably a function of, that varies with w and is independent of time.

One quantity that might fit this restriction is the porosity. The porosity will decrease from the mat surface onward, and if the presence of the septum is ignored, the porosity is time independent in this coordinate system. Thus, one possible interpretation of the curvature in the distribution data is that the collection efficiency is a strong function of the porosity, decreasing as the porosity decreases. The additional curvature at the higher velocities would be ascribed to the smaller porosity that would occur because of the higher compacting loads. To rigorously prove or disprove this hypothesis with the

available data would require an involved calculation to determine what the porosity distribution would be as a function of U_0 and $\underline{w}$, and then take the point values of $\underline{E}$ as determined from the slopes of the retention curves and see if $\underline{E}$ could be made a single valued function of the velocity and the porosity. The data are not sufficiently precise and accurate for such a procedure. It is useful to speculate on whether it is reasonable to expect that the collection efficiency should decrease as the porosity decreases. As the porosity decreases, the local velocity would increase. Earlier work indicates this would lower the collection efficiency. On the other hand, as porosity decreases the void spaces lessen and the particles have a shorter distance to travel to reach a fiber surface. This would tend to increase the collection efficiency. Some air filtration work at the Institute has indicated that the collection efficiency is nearly independent of the porosity below about 0.9. If this is true for the present work, then porosity variation does not explain the curved distribution.

A second possibility that could account for the curvature which was observed in the experimental data is a change in the particle size as the particles pass through the pad. This could also make the collection efficiency a function of $\underline{w}$ but not of time. It is known that TiO_2 particles can flocculate in the presence of the high concentration of sodium chloride used to get retention. It is also known from some preliminary work with a Coulter Counter that the flocculated particles are held together rather weakly and can come apart under the influence of shear stress. It also seems possible, although it would seem to be a smaller possibility, that the particles could actually flocculate as they pass through the pad, due to more frequent collisions. In either case, if the particle size distribution changes as the particles pass through the mat, it is highly probable that the collection efficiency will change also. The direction of the change would depend on the mechanism controlling the rate at which particles strike the fiber surface.

In the Critical Review (1), three different mechanisms for the retention of particles were discussed--interception, impaction, and diffusion. Interception occurs when a particle following a given streamline passes close enough to the fiber surface so that the particle comes in contact with the fiber surface and is retained. It is called interception because the fibers intercept the particles as they flow along the streamlines. In this mechanism, the particles do not leave the streamline that they are on unless they strike the fiber surface. In general, the magnitude of the retention occurring by this mechanism is governed by the ratio of the diameter of the particles to the average pore diameter. As the particles increase in size, the rate of retention by this mechanism would be expected to increase. It would also increase with a decrease in porosity, and would probably be little affected by the velocity. The second mechanism, that of impaction, occurs when, because of their inertia, the particles cross the streamlines as the streamlines bend around the fiber and impact on the fiber surface where they may be retained. The magnitude of the retention which occurs by this mechanism will increase strongly as the velocity is increased, and will also increase with an increase in the particle size. The third mechanism is diffusion, in which the Brownian motion of the particles removes them from their streamlines and they reach the fiber surface. The magnitude of the retention which can occur by this mechanism is dependent on the Brownian diffusion coefficient, which according to the Einstein equation is inversely proportional to the diameter of the particle. Thus, it is to be expected that retention by this mechanism will increase as the size of the particles becomes smaller. Han (1) has made an analysis in which he indicates that for the diffusion mechanism, the collection efficiency decreases as the velocity increases. These three mechanisms are the ones that are discussed most commonly with respect to the retention of small particles. This does not mean that they are the only possible mechanisms

for the transport of small particles from the bulk of the fluid to the fiber surface. Other mechanisms, possibly of an electrokinetic nature, could be active in bringing particles from the bulk to the fiber surface. However, other retention mechanisms are sheer speculation at this time, and the present discussion will be restricted to the three mechanisms which were mentioned above.

The most likely change in the size of the particles as they pass through the mat would be that they become smaller due to breakup of flocs under the shear that exists in the mat during formation. Assuming this to be the case, consider what would happen to the collection efficiency if different mechanisms controlled the retention. If the retention is diffusion controlled, breakup of the flocs into smaller particles would lead to an increase in the diffusion coefficient and an increase in the collection efficiency. This would not explain the present experimental data in which the collection efficiency decreases with an increase in the basis weight coordinate. The other two mechanisms would go in the right direction. Both interception and impaction will tend to decrease as the size of the particles decreases, and the associated lower value of the collection efficiency would be in the direction of the curvature. The fact that the curvature seems to be stronger for the higher velocities would be more likely the case if interception controlled, since the higher velocity could decrease particle size without a corresponding increase in $\underline{E}$ from the velocity as there would be for impaction. Another argument against the impaction mechanism is that the slopes, and hence the collection efficiency, are smaller near the mat surface for the higher velocity. Impaction-controlled retention should give an opposite trend. All of the arguments made above can be reversed if the particles grow as they pass through the mat. In this case, the diffusion mechanism would best explain the observed results. All arguments of this kind must remain in the realm of

speculation until data are obtained on the size distribution of particles reaching and leaving the mat.

A third explanation, in which the net collection efficiency varies as a function of w but not of t, is the possibility of removal of particles which have been already retained by the fluid stresses as the mat is formed. It has been well established that detachment can occur when fluid passes through a mat in which particles have been retained. This being true, it is not hard to understand that the same type of process could occur during the process of mat formation, so that retention and removal of particles go on simultaneously. This problem is not easily handled in terms of the collection efficiency, and really requires adding another mass transfer term to account for the detachment of the particles. It is not now possible to discuss the mathematics of a removal term that would give the type of distributions which were obtained. This could be a quite complex problem. It is shown in Appendix III that a simple detachment term in which the detachment is first order with respect to the bound-particle concentration will not give a saturationlike distribution, but instead gives an exponential distribution to some equilibrium level. This problem has not yet been analyzed in any great detail, but a qualitative argument indicates that detachment could give the type of distribution curve which was observed. If the opportunity for detachment is greater the longer the fiber has been in the mat (larger w in this coordinate system), then the curvature might be due to a detachment process.

One of the tasks left to be done in the near future is a more detailed mathematical analysis of the kind of complicating effects which have been discussed here, namely, what happens when the collection efficiency is a function of w or t or both, and what distributions would be obtained if certain kinds of detachment functions are used. Such analyses would be a great aid in interpreting

distributions which do not fit the idealized cases for which the solutions are known.

One final possible explanation of the curvature of the distribution data is a case in which the collection efficiency is a function of both t and w. This is the effect caused by the presence of the septum. The coordinate w is measured from the upper surface of the mat downward. There are two main advantages to this coordinate system. The first is that the boundary conditions on the particles are fixed at the mat surface. The second reason is that, barring complications, the mat will be stationary in time when viewed from this particular coordinate frame. In this case, the porosity and rate of compression, U_f, will be the same at the same w, no matter at what time in the filtration process one observes it. The presence of the septum destroys this time-independent feature. At the septum, U_f is zero, since it is assumed that the fibers are all caught and there is no loss of fiber at the septum. On the other hand, the velocity of the fiber approaching the mat surface will be that of the suspension, the piston velocity in the present case. Within the mat, the fiber velocity must change between these two values. In an incompressible mat, this change in the fiber velocity occurs as a discontinuity at the mat surface. In this case, U_f will be zero throughout the mat. In a compressible mat, however, the change in fiber velocity occurs throughout the mat. The value of U_f is intimately associated with the compression process. The greatest portion of the change will occur in the front portions of the mat (i.e., where w is small). In the very early stages of mat formation, the change of fiber velocity will be almost discontinuous. As the mat grows, a larger amount of fibers is present to absorb some of the change in U_f. Then the curve of U_f vs. w will become less steep and approach the curve for an infinitely thick mat. Thus, at any given value of w, the relative

velocity of fluid past fiber will be greater at early times than it will be at later times. There will be a tendency for reduced retention in the regions where the relative velocity is highest. The relative velocity would be highest next to the septum throughout the forming process. The cumulative effect would be a smaller rate of retention in the region near the septum. This is in the direction of the distributions which were experimentally observed.

The septum could also affect the retention through flow convergence. In order for the fluid to pass through the septum there must be a convergence of the flow lines so that the fluid can go through the openings in the wire mesh. Thus, in the regions of the mat near the septum, there can be areas in which the average velocity is higher than the filtrate velocity, and other areas which are nearly stagnant. This could have a pronounced effect on the retention in this particular region. Flow convergence would be present in the region near the septum throughout the formation of the pad, and would probably tend to lower the retention in this region. Mathematical analysis of this effect would be difficult since $\underline{E}$ would have to be considered a coupled function of $\underline{w}$ and $\underline{t}$. The expected decrease in the bound-particle concentration in the region near the septum is similar to the distributions which were observed. It would be expected that flow convergence would increase as the velocity increases, which would also be in agreement with the results which have been obtained so far.

It can be seen that there are many possible explanations of the curvature which was observed in the distribution data. Some of these involve changes only in $\underline{w}$, and others are more complex and consist of changes in both $\underline{w}$ and $\underline{t}$. It is possible to distinguish between these two cases experimentally by making a series of pads at the same forming conditions but varying in total basis weight. This could be done by varying the length of the DDT piston stroke or by varying the

total time that the filtration is allowed to proceed in a pump-driven process. In a constant-rate filtration from a homogeneous slurry, the total basis weight is directly proportional to the time that the filtration was in progress. Thus, for this case, the total basis weight of the mat is completely equivalent to the time coordinate. If a series of pads are formed from the same suspension at the same forming conditions but with different total basis weights, a distinction can be made between effects which are a function of $\underline{w}$ alone and those which depend on time also. This could be done by plotting $\underline{P}'$ vs. $\underline{w}$ for all of the pads on the same graph. If the data from all of the pads form a single smooth curve regardless of the total basis weight, then the distributions are functions only of the coordinate $\underline{w}$, and the hydrodynamic effects would be time independent. This would be a useful means for distinguishing between the different possibilities discussed before. If there are deviations from a single smooth plot corresponding to pads of different total basis weight, then the cause of the deviation from the ideal behavior would be a function of time as well as possibly a function of $\underline{w}$.

Although an experiment of this type is, in principle, simple to carry out, this has not been done in the present series of work on the retention problem. The main reason for this is that the DDT as it now exists is limited in the total pressure drop which can be sustained across the mat. In the range of velocities where the deviation from ideal behavior becomes appreciable, the total basis weight of the pad cannot be made much greater than 100 g./m.^{2}. It is possible to make pads of smaller basis weight than this by interrupting the piston before it has completed its stroke; however, this does not readily lead to a solution of the problem stated above. As the sheets become appreciably thinner than 100 g./m.^{2}, it becomes more and more difficult to split the sheets into enough layers so that a meaningful distribution curve can be drawn. There

is also the question about redistribution of particles during the splitting process. A second problem is that as the mats become thinner, the accuracy of the distribution data becomes less because smaller quantities of materials are available for the analysis. In addition, as the mats become very thin, possible complications at the mat surface can become appreciable. Finally, for very thin pads, the initial and final transients due to starting and stopping the piston can be important parts of the whole. For all of these reasons, the experiment described above was not performed. We plan to make the necessary modifications to the equipment and/or procedures so that an experiment of this type can be performed in the next phase of the work on the retention problem.

PRE-PAD RETENTION

Another problem in the recent experiments was the problem of accurately determining the pre-pad retention. Pre-pad retention is a conceptual idea which is difficult to measure experimentally and can be quite difficult to define practically. Its mathematical definition is simple. In any filtration process in which there is to be simultaneous particle retention, it is necessary to have the fiber and particles in intimate contact with one another in suspension before the filtration. Since the fiber and the particles are in intimate contact with one another before the actual filtration occurs, it is entirely possible that there will be some retention of the particles before the mat is formed. Thus, some of the particles that are retained are not necessarily retained during the process of forming the mat. The amount of retention that occurs before the filtration process is called the pre-pad retention. The mathematical definition of the pre-pad retention is quite straightforward. The surface of the mat is defined as a discontinuity in the concentration of the fiber. The pre-pad retention, then, exists merely as a boundary condition on the bound-particle

concentration at the mat surface ($\underline{w} = 0$). According to this definition, the determination of the pre-pad retention is simple. It is necessary only to construct a distribution curve for the mat and extrapolate the curve to the mat surface. The value of the intercept is by definition the pre-pad retention. In practice, the determination is not that simple. In the mathematical treatment of the retention process, a distinction is made between the mat and the suspension, and a discontinuity exists across the mat-suspension interface. It is tacitly assumed that there is no transition zone between the suspension and the mat. In determining the pre-pad retention by extrapolation, it is necessary to assume that the bound-particle concentration is continuous across the interface. In actual fact, such a discontinuous interface does not exist. There is a transition zone in the region near the surface where the system changes from suspension to mat. This transition zone will be at least one fiber length thick, and will begin where the suspension starts to adjust itself to the presence of the mat. If the fibers in the suspension are distributed randomly in space as they approach the mat, the fibers oriented with the streamlines must begin to lay over into a horizontal orientation as the end reaches the surface of the mat. Thus, in the region near the fiber surface, there will be a good deal of reorientation of the fibers, and the beginning of net relative velocity between fluid and fibers. The retention that occurs at this point is difficult to classify as either pre-pad or in-pad retention, and represents a region of uncertainty in determining the pre-pad retention.

A second problem is associated with the suspension itself. In studying retention in fiber mats, one concentrates on describing the conditions that occur during the forming process and neglects the details of the suspension process. The suspension is taken to be a homogeneous system which is at steady state with respect to the time scale of the filtration process. This is done without

considering the details necessary to generate such a homogeneous suspension. Obviously, there must be mixing to keep the fibers and particles from settling out. The rate of retention in the suspension and the steady-state level of pre-pad retention are no doubt dependent on the amount of mixing, and the shear stresses developed by the mixing process. If the average turbulence changes, there will most likely be changes in the concentration of bound particles in the suspension. This is important because these factors will change as the suspension is prepared for the filtration process. In the case of the DDT, the suspension must flow through a large hose down to the DDT itself, pass through a valve into either of two smaller hoses into the flow chamber of the DDT itself. The suspension then sits for a short time in the flow chamber before the filtration is initiated. The steps in this process are difficult to control exactly, and if changes occur in the retention in suspension during this time, this leads to variations in the measured pre-pad retention.

Another problem associated with an independent measurement of the pre-pad retention is the difficulty, if not the impossibility, of measuring the quantity without changing it. In order to measure the pre-pad retention, it is necessary to remove enough fiber from the suspension so that a precise determination of the amount of particles which have been retained can be made. To get an accurate measurement of the pre-pad retention, it is necessary to remove the fibers without changing the concentration of bound particles on them. When collecting these fibers, they must be concentrated to an extent much greater than the concentration of the fibers in the bulk of the suspension. It is impossible to do this without a relative velocity between fibers and particles. In the experiments on the pre-pad retention which were presented earlier in this report, it was noted that the pre-pad retention measured by extrapolating distribution curves was significantly

higher than the same quantity measured by other means. It was also noted that there were fairly large differences in the value of the pre-pad retention in the independent measurements, both within a given method of measuring the retention and between the settling and the thin-pad methods. It appears that it is extremely difficult to get a truly reliable means for measuring the pre-pad retention.

The data which were obtained in the experiment in which the concentration of TiO_2 was varied showed that the pre-pad retention was dependent on the concentration of the TiO_2. On a relative basis, the pre-pad retention in these experiments was practically constant at around 10%. It seems rather strange that the pre-pad retention should be proportional to the concentration of the particles. This behavior suggests some sort of dynamic equilibrium between free and bound particles controlling the level of the pre-pad retention. It is obviously not a case of the fibers being unable to retain more particles. As the amount of TiO_2 in the suspension was increased, the amount of TiO_2 retained as pre-pad retention went up proportionally. There was also additional retention that occurred during the mat formation. It is also obviously not a case of there being insufficient free particles present. About 90% of the particles which were in the suspension were present as free particles. This behavior is strange since it is not at all obvious why an equilibrium should be set up. If the reasons for such an equilibrium were understood, it would undoubtedly add to the understanding of the retention process. It is not at all certain that an equilibrium does in fact exist, although the behavior of the pre-pad retention in that particular experiment is strongly suggestive of an equilibrium. This phenomenon will be studied more thoroughly in the next phase of the retention work.

A possible explanation for an equilibrium is that the pre-pad retention is only weakly attached and comes off easily under the influence of a shear stress. Then an equilibrium may be set up between retention under continual bombardment of free particles and detachment under the shear applied by the mixing process. If this is true, it is very likely that there is a change in the pre-pad retention as the suspension is prepared for the filtration process in the DDT. There could be either a net loss or gain in retention as the suspension is fed to the flow chamber. This might also explain why the settling measurements gave higher values of the pre-pad retention than the thin pads in the pre-pad retention experiment. During the time that the fibers settle, there would be an opportunity for additional retention without much shear to remove particles. This would tend to shift any equilibrium to higher values of the bound-particle concentration.

There is one final factor which might have influenced the values of $\underline{P_o}'$ found from the distribution curves. When the residual suspension was drained out of the flow tube after a pad had been formed, a small amount of the suspension remained above the mat. This small amount of material had to be drained through the pad and could have an effect on the values of $\underline{P_o}'$. However, the amount of material drained through the pad was quite small, and it is doubtful that this would have much of an effect.

The problem of pre-pad retention is not simply an academic question, but has direct practical importance to the papermaker. The question is one of determining where most of the retention occurs on a paper machine. If the retention is mainly pre-pad retention, then it occurs in the mixers, the stock chest, and in the headbox. On the other hand, if most of the retention takes place during the forming process, then the retention is controlled by the sheet-forming conditions, and a greater understanding of the hydrodynamic aspects of the retention process is almost mandatory.

PARTICLE SIZE

In the course of the experiments on the effect of time in suspension on the total retention, it became increasingly evident that the particle system which was being used was not monodisperse and that the particles were flocculating. This discovery was very disquieting when it was made since it makes it difficult to interpret any of the data which have been taken because the particle size during the retention experiments is not known. All of the mechanisms for particle transfer which have been discussed are strongly dependent on the size of the particles. The rate of particle transport by any mechanism will be dependent to a large extent on the size of the particles. Until the time studies were made, it had been tacitly assumed that the TiO_2 particles were on the order of 0.1 to 0.2 micron in diameter, since this was the size that the dispersing technique which was used had been found to give. In retrospect, the possibility of flocculation seems obvious. The physicochemical mechanism of the retention process is essentially a coflocculation process between the fiber and the particles. In order to have a reasonable amount of retention, it is necessary to have the proper ionic conditions to collapse the double layer around the fibers so that particles can be retained. It is now obvious that a colloidal environment that is favorable for the retention of particles on the fiber surface is probably also favorable for the flocculation of the particles. At least, this is true with TiO_2 in salt water. It is also known that the particular colloidal environments used have a strong tendency to flocculate the fibers. Thus, it is reasonable to assume that the same effect would hold true for fines.

The discovery that the particle size was not necessarily remaining constant introduced additional complexity into the retention problem. One of the basic assumptions made at the beginning of this study was that the hydrodynamics

could be studied separately from the colloidal, by holding the colloidal conditions constant at some arbitrary level and changing only the hydrodynamic variables. Colloidal conditions would be controlled by using relatively high concentrations of NaCl in distilled water, using the same sample of fiber throughout, and by preparing the TiO_2 so that it was at the minimum particle size. It was assumed that by starting with the same proportion of the components each time, the colloidal factors would be kept at a constant level. This was not realized because of the flocculation of the particles. The particle size is probably the most important colloidal parameter in the system, and it has not been possible to control it to a particular level. It is now obvious that it is necessary to measure the size of the particles in the environment where they are being used at the time that they are used.

In order to obtain a true understanding of the retention process, it is necessary to know the size distribution of the particles being used. The rate of particle transport to the fiber surface is dependent on the particle size. Without knowledge of the particle size it is impossible to determine the mechanism controlling the retention process. It is generally supposed that retention of particles by fiber mats is governed by Brownian diffusion. This supposition must be verified before the collection efficiency can be broken down into more fundamental components. This cannot be done without knowledge of the particle size. Any attempt to study the fundamentals of the particle transport process requires data on particle size.

A much greater understanding of the process would be obtained if particle size distribution could be easily measured. When there is a distribution of particle sizes, it is expected that the retention process will be selective with regard to particle size so that particles of certain sizes will be preferentially

retained. This would cause a change in the size distribution of the particles which remain. Knowledge of the size of particles which are preferentially retained would be of help in determining the particle transport mechanism. Particle size distribution measurements would also determine whether the size of the particles changes in the mat because of flocculation or deflocculation.

Measurements of particle size distributions are planned for the next phase of the retention work. A Coulter Counter has been obtained for making these measurements. This device works on an electronic gating principle and offers a rapid method (order of 10 minutes) for determining the size distribution of a particle system. Preliminary work with the Coulter Counter on TiO_2 has demonstrated that the instrument is able to detect flocculated TiO_2 particles. Since the aperture on the Coulter Counter is easily plugged by fibers, particle size determinations must be made in the absence of fibers. This problem can be handled by making permeation experiments. In permeations, the mat is formed first, and then a particle suspension is passed through the pad. The particle size measurements can then be made on the suspension before and after it permeates the pad. Experiments of this type would give information on selective retention, and hence on the retention mechanism. It would also indicate any flocculation or deflocculation occurring in the mat. It is also planned to measure the size distribution of particles in the filtrate leaving the DDT. Information from permeation experiments would be needed to interpret these data.

SHEET SPLITTING

One of the problems which was present in almost all of this work was the possible redistribution of particles which occurs when the Beloit sheet splitter is used to split the pads. The data from the thick pads which were

partially hand split and partially Beloit split definitely show a small change in the particle distribution due to the Beloit sheet splitter. The effect is small. The amount of particle redistribution is not very great. However, the redistribution does appear to be significant compared to the accuracy required to quantitatively understand the complex effects which were observed. A better method of splitting the sheets is required.

One of the basic assumptions made at the start of this program on retention was that the Beloit sheet splitter could be used to delaminate the pads which were formed. It now appears that the Beloit sheet splitter cannot be used when precise retention data are required. Some other means of splitting the sheet will have to be used. The thin pads which are formed on the DDT are not amenable to hand splitting. Thus, a new sheet-splitting method will have to be developed. No actual work on this problem has been done to date. Work on splitting methods is planned for the near future. If a new method cannot be found, the Beloit splitter will have to be used, and the data used with reservations.

WEB FORMER RETENTION

The final results to be discussed are the retention runs on the Web Former. These experiments were of a preliminary nature to observe the kinds of retention data which could be obtained and to determine the best way to run the Web Former for future experiments. The experiments were not intended to give detailed, quantitative retention data under web-forming conditions.

The most interesting data are from the run in which the basis weight of the sheet and the pressure drop across the forming zone were varied. When the basis weight was varied at a constant pressure drop, the average bound

particle concentration increased as the basis weight increased. The increase was slightly greater than linear. This is indirect evidence that pronounced particle distributions exist within the sheet. (They would be roughly twice as steep as the average curve.) Actual distributions within the sheet were not measured since the samples were not split. The slight upward curvature indicates the average collection efficiency increased as the mat thickness increased. This is reasonable since a higher basis weight would lead to a lower average forming velocity and a higher collection efficiency.

Extrapolation of the bound-particle-concentration curve to zero basis weight indicates that the pre-pad retention is quite small compared to the total retention. This means that the great bulk of the retention occurred during the sheet-forming process. This is encouraging since it underlines the importance of understanding retention under sheet-forming conditions. The low amount of pre-pad retention may have been due to the peculiar furnish (no salt, high TiO_2 concentration) used for this experiment. However, earlier work has shown that colloidal conditions which increase the pre-pad retention also tend to increase the collection efficiency. Thus, the relative amounts of pre-pad and in-pad retention may be indicative of a general situation. In any event, the Web Former data are direct evidence, for one case at least, that the retention occurring during sheet formation can be dominant.

The pressure drop over the forming zone had a very pronounced effect on the retention obtained on the Web Former. This is due to at least two effects. When a sheet of a given basis weight is formed at a higher pressure drop, the average velocity during the forming process will be higher. This would be expected to decrease the retention. In addition, as the pressure drop is increased, the amount of air which would be pulled through the sheet would be

expected to increase. This would result in increased removal of particles, and a decrease in the net retention.

The most significant feature of the Web Former retention data is that all of the trends which were observed are in agreement with what is expected from theoretical considerations. None of the behavior can be classified as strange. The data are only overall measurements and do not include details of the distributions within the sheet. Thus, some of the more complex behavior could not be detected in these preliminary runs. However, the data which have been obtained appear to substantiate the method of attack which has been used on the problem of particle retention.

NOMENCLATURE

$\underline{A}$ = cross-sectional area of a mat or sheet sample, cm.^{2}

$\underline{C}$ = free-particle concentration, mass free particles per unit volume fluid, g./cc.

$\underline{C}'$ = bound-particle concentration, mass bound particles per unit volume fiber, g./cc.

$\underline{D}$ = detachment coefficient, sec.$^{-1}$

$\underline{E}$ = collection efficiency, dimensionless

$\underline{L}$ = position of mat surface in $\underline{z}$ coordinate system, cm.

$\underline{m}$ = fiber mass coordinate, mg.

$\underline{N}$ = mass flux of free particles past a fiber layer, g./cm.^{2} sec.

$\underline{N}'$ = net mass flux of particles becoming bound at the fiber surface, g./cm.^{2} sec.

$\underline{P}$ = free-particle concentration, mass particles per unit mass fluid, dimensionless

$\underline{P}'$ = bound-particle concentration, mass particles per unit mass fiber, dimensionless

$\underline{P}_o$ = free-particle concentration in suspension on mass basis, dimensionless

$\underline{P}_o'$ = pre-pad retention, mass particles per unit mass fiber, dimensionless

$\underline{P}_{oo}$ = total concentration of particles in system, mass particles per unit mass fiber, dimensionless

$\underline{P}'_{eq}$ = equilibrium bound-particle concentration in detachment case, dimensionless

$\underline{R}$ = particle mass transfer rate, net mass rate becoming bound per unit volume mat, g./cc. sec.

$\underline{S}$ = hydrodynamic specific surface, cm.^{2}/g.

$\underline{s}$ = consistency, mass fiber per unit mass fluid, dimensionless

$\underline{t}$ = time, sec.

$\underline{U}_o$ = filtrate velocity, cm./sec.

$\underline{U}_f$ = superficial fiber velocity, cm./sec.

$\underline{U}_w$ = superficial fluid velocity, cm./sec.

U_{f_o} = superficial fiber velocity at septum, cm./sec.

W = total basis weight of mat at any stage of formation, g./m.^{2}

w = basis weight coordinate, measured from mat surface, g./m.^{2}

z = position coordinate, cm.

ϵ = interfiber porosity, dimensionless

ρ_f = fiber density, g./cc.

ρ_{f_o} = fiber density at septum, g./cc.

ρ_w = fluid density, g./cc.

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APPENDIX I

DERIVATION OF THE RETENTION EQUATIONS

The mathematical treatment of the retention of small particles by fiber mats is based on the application of continuity principles to the process. In formulating the problem, a distinction is made between free and bound particles. Free particles are associated with the fluid and are not considered as retained. Bound particles are attached to the fiber surface and are considered to be retained. The retention process itself is considered to be a mass transfer process between particles in the free state and particles in the bound state.

The mathematical description of retention starts with four continuity equations. These are for fiber, fluid, free particles, and bound particles, respectively.

$$\frac{\partial}{\partial z} \rho_f U_f = \frac{\partial}{\partial t} \rho_f (1 - \epsilon) \qquad (7),$$

$$\frac{\partial}{\partial z} \rho_w U_w = \frac{\partial}{\partial t} \rho_w \epsilon \qquad (8),$$

$$\frac{\partial}{\partial z} C U_w = \frac{\partial}{\partial t} C\epsilon + R \qquad (9),$$

$$\frac{\partial}{\partial z} C' U_f = \frac{\partial}{\partial t} C'(1 - \epsilon) - R \qquad (10),$$

where

ρ_f = density of the fiber,

ρ_w = density of the fluid (water),

U_f = superficial fiber velocity, volumetric fiber flux (positive value),

U_w = superficial fluid velocity, volumetric fluid flux (positive value),

ϵ = interfiber porosity,

C = concentration of free particles, mass per unit volume of fluid,

C' = concentration of bound particles, mass per unit volume of fiber,

R = particle mass transfer rate, net rate of conversion of free particles to bound particles per unit volume of the mat,

t = time coordinate, and

z = position coordinate, measured up from septum.

There are few restrictions on these equations. The main question with regard to their validity is the applicability of differential continuity principles to a system of fibers which are discrete quantities. In this treatment, the validity of the continuity principle is assumed. The ultimate test of the validity of the equations rests with their ability to predict experimental data.

The essence of the retention process is the mass transfer rate, R. In proceeding with the development of the retention equations, it is desirable to express the mass transfer rate in terms of quantities that can be measured. This leads to a general definition of the collection efficiency.

Assume that the fiber can be characterized by a surface area per unit mass, S. Then, if a differential layer of thickness dz is considered, the fiber surface area in this layer will be $S\rho_f(1 - \epsilon)Adz$, where A is the cross-sectional area of the mat under consideration. If N' is defined as the net mass flux of particles becoming bound at the fiber surface, the rate at which particles become bound in the differential layer is $N'S\rho_f(1 - \epsilon)Adz$. R is defined as the net rate of mass transfer per unit volume of the mat; hence, $RAdz = N'S\rho_f(1 - \epsilon)Adz$, or $R = N'S\rho_f(1 - \epsilon)$. This reduces the problem of determining

$\underline{R}$ to the problem of determining $\underline{N}'$, the net particle flux at the fiber surface. This is done by defining the collection efficiency, $\underline{E}$, by the relation

$$E = N'/N \tag{11}$$

where $\underline{N}$ is the flux of free particles past the fiber. Since both the fluid and the fiber are in motion in general, $\underline{N}$ must take into account the relative motion of the fluid past the fiber. In terms of superficial velocities, $\underline{N} = \underline{C}[\underline{U_w} - \epsilon\underline{U_f}/(1 - \epsilon)]$. Then the net particle mass transfer rate can be expressed as

$$R = (1 - \epsilon)\rho_f S[U_w - \frac{\epsilon U_f}{(1 - \epsilon)}]EC \tag{12}$$

.

It should be noted that the definition of $\underline{E}$ in this development is completely equivalent to the definition of $\underline{E}$ in the earlier work. Defined as it is here, it is clear that $\underline{E}$ is essentially a dimensionless mass transfer coefficient.

Although all of the elements of retention are present in Equations (7-12), the $\underline{z}$-$\underline{t}$ coordinate system is not the best coordinate system for studying retention. There are several reasons for this. In this coordinate system, the retention boundary conditions occur on a moving mat surface. This is difficult to treat mathematically. Another problem is that retention measurements are not made with respect to position, and in a compressible system the position does not correspond to a particular fiber layer. Thus, it is desirable to have the retention equations written in a coordinate system in which the coordinates are experimentally measurable and the boundary conditions apply at fixed values of the coordinates. A coordinate system which fulfills these qualifications is the $\underline{w}$-$\underline{t}$ system where $\underline{w}$ is the basis weight of the mat from the mat surface to the point of interest.

If the surface of the mat is defined by $\underline{z} = \underline{L}(\underline{t})$, the coordinate $\underline{w}$ is defined by the equation

$$w = \int_{z}^{L(t)} \rho_f(1 - \epsilon)dz = W(t) - \int_{o}^{z} \rho_f(1 - \epsilon)dz \qquad (13)$$

where $\underline{W}(\underline{t}) = \int_{o}^{\underline{L}(\underline{t})} \rho_{\underline{f}}(1 - \epsilon)d\underline{z}$ = total basis weight of the mat at any stage in the formation. In converting the continuity equations from the $\underline{z} - \underline{t}$ coordinate system to the $\underline{w} - \underline{t}$ system, the following transformations are required:

$$\frac{\partial}{\partial z} \Rightarrow -\rho_f(1 - \epsilon)\frac{\partial}{\partial w} \quad \text{and}$$

$$\frac{\partial}{\partial t} \Rightarrow \frac{\partial}{\partial t} + \left[\frac{dW}{dt} - \rho_f U_f + \rho_{f_o} U_{f_o}\right]\frac{\partial}{\partial w} .$$

Using these transformations and the expression for $\underline{R}$ in Equation (12), Equations (7), (8), (9), and (10) become

$$-\rho_f(1 - \epsilon)\frac{\partial}{\partial w}\rho_f U_f + \left[\rho_f U_f - \rho_{f_o} U_{f_o} - \frac{dW}{dt}\right]\frac{\partial}{\partial w}\rho_f(1 - \epsilon) = \frac{\partial}{\partial t}\rho_f(1 - \epsilon) \qquad (14)$$

$$-\rho_f(1 - \epsilon)\frac{\partial}{\partial w}\rho_w U_w + \left[\rho_f U_f - \rho_{f_o} U_{f_o} - \frac{dW}{dt}\right]\frac{\partial}{\partial w}\rho_w \epsilon = \frac{\partial}{\partial t}\rho_w \epsilon \qquad (15)$$

$$-\rho_f(1 - \epsilon)\frac{\partial}{\partial w} C U_w + \left[\rho_f U_f - \rho_{f_o} U_{f_o} - \frac{dW}{dt}\right]\frac{\partial}{\partial w} C\epsilon = \frac{\partial}{\partial t} C\epsilon + \rho_f(1 - \epsilon)ES\left[U_w - \frac{\epsilon U_f}{(1 - \epsilon)}\right]C \qquad (16)$$

$$-\rho_f(1 - \epsilon)\frac{\partial}{\partial w} C' U_f + \left[\rho_f U_f - \rho_{f_o} U_{f_o} - \frac{dW}{dt}\right]\frac{\partial}{\partial w} C'(1 - \epsilon) = \frac{\partial}{\partial t} C'(1 - \epsilon) - \rho_f(1 - \epsilon)ES\left[U_w - \frac{\epsilon U_f}{(1 - \epsilon)}\right]C \qquad (17) .$$

For the case where $\rho_{\underline{f}}$ and $\rho_{\underline{w}}$ are constants, Equations (14) and (15) can be combined. This is not too restrictive an assumption. Since $\rho_{\underline{f}}$ is the density of a swollen fiber, it may be expected to change somewhat under a load. However, this would be a minor effect. To be completely general, if $\rho_{\underline{f}}$ is

allowed to change as a function of pressure, an additional source term would have to be put into the fluid continuity equation to account for the fluid squeezed out of the fiber. This greatly complicates the equations without adding any significant effects. Thus, constancy of ρ_f is implied when writing the original continuity equations, so the assumption is justified.

Assuming ρ_f and ρ_w are constants, and adding Equation (14) to Equation (15), yields

$$-\rho_f(1 - \epsilon) \frac{\partial}{\partial w} (U_f + U_w) = 0 \qquad (18) .$$

Hence, the following is obvious:

$$U_f + U_w = U_o \qquad (19)$$

where U_o is the filtrate velocity and is at most a function of time, independent of w. Equation (19) is used to eliminate U_w from the equations.

The retention equations which are desired are equations describing the free- and bound-particle concentrations. To obtain these, the product terms in Equations (16) and (17) are broken into parts, and the terms involving $C(\partial U_w/\partial w)$, $C(\partial \epsilon/\partial w)$, $C'(\partial U_f/\partial w)$, and $C'[\partial(1 - \epsilon)/\partial w]$ are eliminated by using Equations (14) and (15). Then Equations (16) and (17) become:

$$-\left[u_o - \frac{U_f}{(1 - \epsilon)} + \frac{\epsilon}{\rho_f(1 - \epsilon)} \left(\frac{dW}{dt} + \rho_{f_o} U_{f_o}\right)\right] \frac{\partial C}{\partial w} = \frac{\epsilon}{\rho_f(1 - \epsilon)} \frac{\partial p}{\partial t} + SE \left[u_o - \frac{U_f}{(1 - \epsilon)}\right] C \qquad (20)$$

$$-\left[\frac{dW}{dt} + \rho_{f_o} U_{f_o}\right] \frac{\partial C'}{\partial w} = \frac{\partial C'}{\partial t} - \rho_f SE \left[u_o - \frac{U_f}{(1 - \epsilon)}\right] C \qquad (21) .$$

Now, dW/dt is the rate at which the basis weight of the mat is changing in time and $\rho_{f_0} U_{f_0}$ is the rate at which fiber is lost at the septum. The sum of these two quantities must be equal to the rate at which fiber is supplied to the surface of the mat. To a very good approximation, the rate at which fiber is supplied to the mat surface is $\rho_w s U_0$ where s is the consistency. Thus, $\rho_w s U_0 = dW/dt + \rho_{f_0} U_{f_0}$. One other change which is convenient to make is to put the particle concentration on a mass basis by defining $P' = C'/\rho_f$ and $P = C/\rho_w$. Then Equations (20) and (21) can be written as

$$-\left[U_0 - \frac{U_f}{(1-\epsilon)} + \frac{\rho_w U_0 s \epsilon}{\rho_f (1-\epsilon)}\right] \frac{\partial P}{\partial w} = \frac{\epsilon}{\rho_f (1-\epsilon)} \frac{\partial P}{\partial t} + SE\left[U_0 - \frac{U_f}{(1-\epsilon)}\right] P \quad (1)$$

$$-\rho_w U_0 s \frac{\partial P'}{\partial w} = \frac{\partial P'}{\partial t} - \rho_w SE\left[U_0 - \frac{U_f}{(1-\epsilon)}\right] P \quad (2).$$

These are the basic retention equations.

APPENDIX II

SOLUTIONS FOR THE RETENTION EQUATIONS

The retention equations which were derived in Appendix I are a set of general partial differential equations for free and bound particles. To be useful in studying retention they must be solved. A general solution to these equations is not now available. However, they can be solved for some special cases, and the results are quite useful in interpreting retention phenomena.

PERMEATION

The first case for which a solution can be obtained is that of permeation. In this case, the pad is formed first and is then permeated with a particle suspension. The first feature of a permeation case is that the terms which involve the consistency are automatically zero. In addition, compressibility effects will be very minor, particularly if the mat is subject to externally applied loading. Then $\underline{U_f}$ is negligible and the retention equations become:

$$-\frac{\partial P}{\partial w} = \frac{\epsilon}{\rho_f(1-\epsilon)U_o}\frac{\partial P}{\partial t} + SEP \qquad (22)$$

$$\frac{\partial P'}{\partial t} = \rho_w U_o SEP \qquad (23) .$$

The boundary conditions which are applicable are

$$P = P_o \quad \text{at} \quad w = 0 \qquad \text{and} \qquad P' = 0 \quad \text{at} \quad t = 0 .$$

It is necessary to solve Equation (22) before Equation (23). If the concentration of free particles in the suspension, $\underline{P_o}$, is independent of time, i.e., the boundary condition is stationary, the time dependency in Equation (22) will enter

in only during the initial transient when the particle suspension first penetrates the mat. For a permeation which is carried out for a long period of time compared to the initial transient, this time dependency can be neglected. The solution to Equation (22) can then be written directly,

$$P = P_0 e^{-SEw} \qquad (3),$$

and Equation (23) is solved by substituting in Equation (3) and integrating to give:

$$P' = P_0 t \rho_w U_b SE e^{-SEw} \qquad (4).$$

Equations (3) and (4) are the solutions to the retention equations for the case of a permeation. The free-particle concentration decreases exponentially away from the mat surface. The bound particles are distributed in the mat in the same exponential fashion as the free particles. The amount of bound particles at any position increases linearly with time and with the collection efficiency.

CONSTANT-RATE FILTRATION

The second case which allows a solution to the retention equations is a constant-rate filtration to form a pad from a homogeneous suspension. In this case, the term in which consistency appears will be significant in the bound-particle equation. It is again assumed that $\underline{U_f}$ is negligible compared to $\underline{U_b}$. Since the filtration is from a homogeneous suspension, the boundary conditions $\underline{P} = \underline{P_0}$ at $\underline{w} = 0$ and $\underline{P'} = \underline{P_0}'$ at $\underline{w} = 0$ are stationary. In the absence of complicating effects, i.e., $\underline{E}$ constant and septum effects negligible, the time derivative terms will be negligible. This is because in this coordinate system, the process is steady. Then the retention equations simplify to:

$$-\frac{\partial P}{\partial w} = SEP \tag{24}$$

$$\frac{\partial P'}{\partial w} = \frac{SE}{s} P \tag{25},$$

with the boundary conditions $\underline{P} = \underline{P_o}$ at $\underline{w} = 0$ and $\underline{P'} = \underline{P_o}'$ at $\underline{w} = 0$. The solution to Equation (24) is Equation (3), the same as for the permeation case. Putting this into Equation (25) gives:

$$\frac{\partial P'}{\partial w} = \frac{SE}{s} P_o e^{-SEw} \tag{26}.$$

This can be integrated to give

$$P' = P_o' + \frac{P_o}{s}\left[1 - e^{-SEw}\right] \tag{5}.$$

Equation (5) gives the distribution of bound particles for the ideal case of a constant-rate filtration. The distribution still retains an exponential dependency, but it is very different from the free-particle distribution. The free-particle concentration is highest at the mat surface and decreases exponentially away from the surface. The bound-particle concentration is lowest at the mat surface and rises with a gradually decreasing rate away from the surface. The dominant feature of the bound-particle distribution is that the parts of the mat laid down first (largest $\underline{w}$) retain the most particles. This can be shown by expanding out the exponential in Equation (5):

$$P' = P_o' + \frac{P_o}{s}\left[1 - 1 + SEw - \frac{S^2E^2w^2}{2} + \ldots\right] \tag{27}.$$

The first nonzero term gives

$$P' = P_o' + \frac{P_o}{s} SEw \tag{6}.$$

This term which is linear in basis weight is due to the greater opportunity for retention in the portions of the mat which are laid down first. The higher order terms, representing curvature away from the linear dependence, account for the change in free-particle concentration in the mat. This can be easily shown. If the change in free-particle concentration is neglected, $\underline{P}_o$ can be substituted for $\underline{P}$ in Equation (25). Then Equation (25) can be solved to give $\underline{P} = \underline{P}_o' + (\underline{P}_o/\underline{s})\underline{SEw}$ which is identical to Equation (6). Thus, a linear increase with basis weight represents the effect of different portions of the mat being laid down at different times. The higher order terms represent reduced retention due to a decrease in free-particle concentration.

APPENDIX III

SIMPLIFIED TREATMENT OF PARTICLE DETACHMENT

In obtaining the basic retention equations [Equations (1) and (2)], the retention process was treated as a mass transfer process. The net rate of transfer of particles from the free to the bound state per unit volume of the mat was written as

$$R = \rho_f(1 - \epsilon)SE\left[U_0 - \frac{U_f}{(1 - \epsilon)}\right]\rho_w P \qquad (28) .$$

It is possible to consider detachment within the framework of this equation by letting $\underline{E}$ become negative. However, when $\underline{R}$ is written as above it is implied that $\underline{E}$ is not a function of $\underline{P}$ or $\underline{P}'$. This is obviously not true for detachment. Equation (28) in reality describes the attachment process, and if $\underline{R}$ is to be treated as the net rate of particle transfer, a term describing detachment should be added on.

In order to keep the mathematical structure which has been used so far, a term which describes the rate of particle detachment per unit volume of the mat is required. It is reasonable to assume that the rate of detachment is dependent on the concentration of bound particles. As a first approximation, the rate of detachment can be taken as directly proportional to the bound-particle concentration. Then the detachment rate can be written as $\rho_f(1 - \epsilon)\underline{D}P'$. Here $\underline{D}$ is a detachment coefficient with dimensions of inverse time. No attempt will be made now to attach any deeper significance to $\underline{D}$. With this representation of the detachment rate, $\underline{R}$ can be written as

$$R = \rho_f(1 - \epsilon)\{SE[U_0 - \frac{U_f}{(1 - \epsilon)}]\rho_w P - DP'\} \qquad (29) .$$

Then the retention equations become:

$$-\left\{U_o - \frac{U_f}{(1-\epsilon)} + \frac{\rho_w U_o s\epsilon}{\rho_f(1-\epsilon)}\right\}\frac{\partial P}{\partial w} = \frac{\epsilon}{\rho_f(1-\epsilon)}\frac{\partial P}{\partial t} + SE\left[U_o - \frac{U_f}{(1-\epsilon)}\right]P - \frac{DP'}{\rho_w} \quad (30)$$

and

$$-\rho_w U_o s\frac{\partial P'}{\partial w} = \frac{\partial P'}{\partial t} - \rho_w SE\left[U_o - \frac{U_f}{(1-\epsilon)}\right]P + DP' \quad (31).$$

For the ideal case of a constant-rate filtration, as was discussed previously, and for $\underline{E}$ and $\underline{D}$ constant during the forming process, these equations can be simplified to

$$-\frac{dP}{dw} = SEP - \frac{DP'}{\rho_w U_o}, \qquad P = P_o \text{ at } w = 0 \quad (32)$$

$$-s\frac{dP'}{dw} = -SEP + \frac{DP'}{\rho_w U_o}, \qquad P' = P_o' \text{ at } w = 0 \quad (33).$$

Adding these equations together gives

$$\frac{-dP}{dw} - s\frac{dP'}{dw} = 0 \quad (34).$$

This can be immediately solved and the boundary conditions applied to give

$$P + sP' = P_o + sP_o' = sP_{oo} \quad (35).$$

Equation (35) can be used to eliminate $\underline{P}$ in Equation (33), which can then be solved to give

$$P' = P_o' + \left\{\frac{SEP_o - \frac{DP_o'}{\rho_w U_o}}{SEs + \frac{D}{\rho_w U_o}}\right\}\left\{1 - e^{-[SE+(D/\rho_w U_o S)]w}\right\} \quad (36).$$

The complex-looking distribution given by Equation (36) is very similar to the distribution which is obtained for the case of no detachment. The functional dependence on $\underline{w}$ is the same. In the case of no detachment, the bound-particle concentration asymptotically approaches the value in which all particles are retained, i.e., $\underline{P}'(\underline{w} \rightarrow \infty) = \underline{P_o}' + \underline{P_o}/\underline{s}$. In the case of detachment, the bound-particle concentration asymptotically approaches an equilibrium value given by $\underline{P}'_{eq} = [\underline{SE}(\underline{P_o} + \underline{sP_o}')]/[\underline{SEs} + (\underline{D}/\rho_{\underline{w}}\underline{U_b})]$. This equilibrium is determined by the conditions at which the rate of attachment equals the rate of detachment.

It is important to realize that for this simplified case, the distributions are very similar to the case of no detachment, except for the different concentrations at which no more retention occurs. This does not seem to be the type of behavior which has been observed in retention experiments. Thus, if detachment is the cause of the effects which were observed, the detachment process is probably more complicated than simply first order with respect to the bound-particle concentration.